Politecnico di Torino

1859

IAM Integrated Additive Manufacturing@PoliTo

Visual communication of metal AM

In method of Timeline, Gigamap and interactive site

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The origin of AM

01

Chapter

1.
The origin of AM

AM is not a new technology, and it has been dedicated to industrial production for nearly 30 years, but at that time, it was called additive manufacturing technology. In recent years, AM has developed into a more mature technology and many people think it is a sudden new technology, but in fact, AM has spanned three centuries. From the very beginning of manual layer-by-layer to the current fully automated machine printing, the development of AM has been amazing.

The prototype of thinking about three dimensional layered objects date back to 4000 years ago, when lacquerware was excavated in China used a bonding agent to lay silk and hemp on the bottom tire, and then dug up the bottom tire to shape it after the lacquer is dried. The ancient Egyptians cut the wood into boards and re-layered them to make a laminated material like modern plywood before in B.C.[1]

Additive manufacturing was initiated in 1940, when Perera proposed cutting and bonding cardboard layer by layer to create a simulated three-dimensional topographic map. The '80 was marked by the invention of light-curing technology (SLA) by Hull, and the establishment of 3D Systems, the world's first additive manufacturing company, additive manufacturing technology gradually came into reality from the ideal and successively.

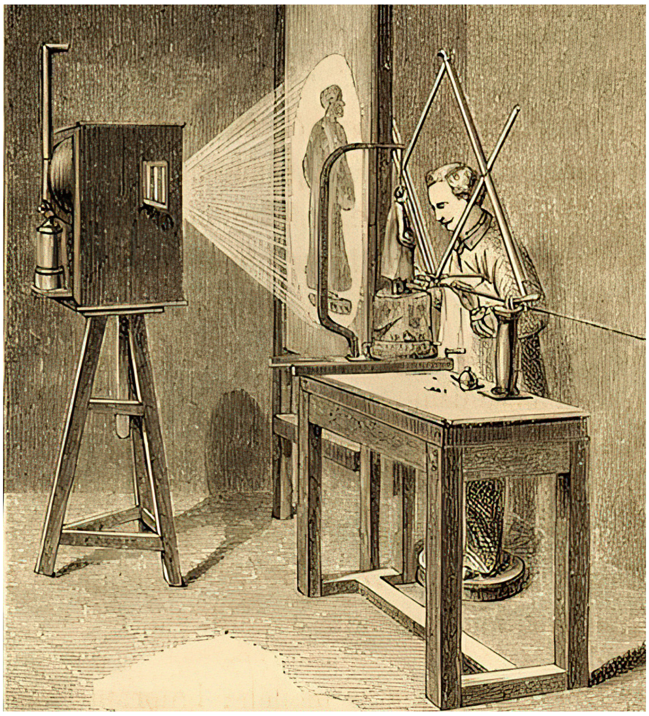
After 2000, the metal additive manufacturing technologies emerged, such as laser selective melting (SLM), laser near-net forming (LENS), et cetera. The weak points of ultracomplex processing that cannot be achieved by traditional manufacturing has been solved almost perfectly and successfully led to additive manufacturing to the stage of large-scale industrial trial and application. Compared with traditional manufacturing industries, its process, equipment, production line, factory model and upstream and downstream industry chains are still under constant updating and improvement. It has been verified and recognized by many industries such as aerospace, military, automotive and medical.

At present, the technology route of additive manufacturing is gradually finalized, the industry standardization and rules are gradually clarified, the process parameters are continuously calibrated through experiments, and the process flow is continuously optimized and innovated, making the finished products of additive manufacturing more and more mature, and their performance indexes have approached or even surpassed those of cast and forged products. Additive manufacturing products are gradually accepted by more industries, and the scale of promotion and application has led to the gradual reduction of costs.

Plastic 3D Printing with EOS

1.1
The story of the plastic AM

After 2000, the metal additive manufacturing technologies emerged, such as laser selective melting (SLM), laser near-net forming (LENS), et cetera. The weak points of ultra complex processing that cannot be achieved by traditional manufacturing has been solved almost perfectly and successfully led to additive manufacturing to the stage of large-scale industrial trial and application. Compared with traditional manufacturing industries, its process, equipment, production line, factory model and upstream and downstream industry chains are still under constant updating and improvement. It has been verified and recognized by many industries such as aerospace, military, automotive and medical.


François Willème in 1859

However, the first use of photosensitive polymers were in 1972, Matsubara from Mitsubishi Motors based on cardboard lamination technology. It takes advantage from light-curing materials, photosensitive polymer resin coated on top of refractory particles, and then these particles were filled to the laminated layer. Subsequently, when heated, a layer corresponding to the stacked one is created, and the existing selective gaze was projected onto this layer to harden the specified part. While the un-scanned part would be dissolved using a chemical solvent, but this method was only applicable to the production of conventional processes and challenging to process surfaces.

The time came in 1984, the first appearance of SLA 3D printing technology; Charles Hull invented and patented stereolithography (SLA). The method uses light to catalyze a photosensitive resin that is then molded. Hull is also known as the "father of 3D printing"; in fact, he founded 3D Systems, the world's first 3D printing equipment vendor. The company then developed the famous STL file format, which triangulates CAD models and has become one of the industry standards for CAD/CAM system interface file formats.
In 1986 the Laminated Object Manufacturing (LOM) was also invented. The National Science Foundation (NSF) sponsored Helisys to develop LOM (Laminated Object Manufacturing), which works by cutting and glueing sheets of material into shape.

In 1988, Scott Crump, an American, invented FDM (Fused Deposition Modeling), which

works by using high temperatures to melt the material and then spray it out to re-solidify it.
In 1989, FDM technology pioneer Scott Krupp founded Stratasys Corporation, marking the commercialization of SLA technology.
In 1991, the U.S. company Stratasys released the first fused deposition molding machine, the U.S. company Helissy launched the first laminated method of rapid prototyping (LOM) equipment, the same year in Israel's Cubital invented the surface exposure process (Solid Ground Curing) curing technology.

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The world's first 3D Printer designed by Charles Hall in 1984 on display at the National Inventors Hall of Fame

1.2
From plastic AM to metal AM

As we all know, plastic materials have been developing in the direction of high strength, by enhancing the strength of plastic used to directly replace metal for all kinds of complex components, both cheap and light, so that plastic materials are widely used in 3d printing manufacturing. In addition, plastic materials can also avoid defects to composite, functional direction, especially to achieve multi-material composite, and then give plastic-specific functions.

In the early 1990s, additive manufacturing processes shifted into metal processing, with the earliest attempts being laser powder bed methods using metal powders as raw materials and CO2 lasers for consolidation. However, the laser power was not powerful enough to sufficiently compact and solidify the metal powder, so the products produced had to be sintered with a low density values, making them unsuitable for largescale industrial use.

Metal 3D printing can serve the manufacturing of metal parts for high-end manufacturing industry, which is disruptive and has great potential for development. While non-metal 3D printing usually uses plastic and resin materials, metal 3D printing usually uses various alloy powders and wires. In addition to the advantages of non-molded and customizable metal 3D printing, it can complete the printing of highly complex and high-precision parts that cannot be manufactured by traditional processes, and has good development potential. Metal 3D printing has a promising future in aerospace,

Junkers J 1 in 1915

medical denture and implant manufacturing, automotive and other applications. Plastic AM can be divided into two process categories; the first is a powder or liquid bed-based system fusing or curing the material using a laser or heat source. The second is depositing material by extruding through nozzles or by print heads.[3] The inspiration from these two technologies has led to ways in which metal printing can be developed.

n the 1910s-1950s, the widespread use of metals in military applications, such as ship and aircraft construction, drove the development of welded processes in steel, aluminium and titanium alloys. In the 1940s gas tungsten arc welding and gas metal arc welding were developed. Electron beam welding was invented in the 1950s.The These technologies also drive the passage from plastic AM to metal AM. Before metal AM arrives, we need to mention two methods of metal technology.

The first is weld cladding. In many industrial processes, corrosive and abrasive media can cause damage to piping systems and other installations. For example, in oil and gas production, components are subject to severe wear due to sand friction; chemical equipment is also severely damaged by direct contact with aggressive substances. The higher the operating temperature and pressure, the more pronounced the erosion. To increase the resistance of these highly exposed parts, the surfaces are welded with non-corrosive materials to increase surface protection. Cladding is applied whenever long service

Weld cladding

life is expected from expensive components or when the workpiece cannot be produced entirely from the proper wear-resistant material. However, this technique has limitations, requiring a large melt pool, usually, only flat deposition and high total heat resulting in heat build-up.

The second one is powder metallurgy, a processing method in which metal powders are used as raw materials. These are pressed and sintered to produce the final part. The powder metallurgy process consists of three main steps: first, the main material component is broken down into many fine particles of powder; then, the powder is loaded into the mold cavity, and a certain pressure is applied to form a pressed billet with the required part shape and size; finally, the pressed billet is sintered.

Significant technology development has occurred in the production of powder materials, powder characterization, and the characterization of sintered metal materials and parts. Much of what has been learned is directly or indirectly applicable to AM sintering or AM fusion processing and is helping to create new industry standards.[4]
As plastic AM technology continues to advance in terms of applications and access to the manufacturing value chain, the development of computers is constantly being updated. These two technologies have largely inspired the creation of AM metal as a the paradigm for metal manufacturing, allowing the development of metal printing with significant developments, and more tangible requirements - the need for a high energy source as a source to melt the metal, the need to turn the metal into a powder, which is a gradual progression from plastic printing to metal.

In the mid-1990s, the development of lasers capable of delivering the high amounts of energy that are needed for processing metal powders in sintered or fused states paved the way for the development of a the process is known as direct metal laser sintering (DMLS). The latter is an SLS extension to metals that started to be developed in the late 1980s by Carl Deckard (1989) for the additive manufacturing of polymers.[5] DMLS technology, as a branch of SLS technology exploit the same principle. However, DMLS technology is more difficult to accurately form complex-shaped metal parts.

Parts made by DMLS

Powder metallurgy

1.3
The metal feedstock

Conventional metal powders such as those produced by water atomization are angular, irregular, or agglomerated, so gas atomization is preferred.[6] Powders currently can be used in AM most commonly range from 10 to 105 microns in size and are generally spherical in shape, powder suit for bed machines to spread fine layers of powders evenly and powder feed systems to deliver an inert gas-fed stream of powder smoothly without nozzle clogging.[7] But the metal AM the process requires no tooling - it uses powder to manufacture components in a similar way to an inkjet printer. It breaks the part into many 2D layers and prints the finished component layer by layer.

The range of materials available for metal AM systems are continuing to expand. Commonly used materials are stainless steel, aluminium, nickel, cobalt-chromium, and titanium alloys. Many machine manufacturers offer their materials. Not all materials can be used for AM, but in many cases, available metal powders for specific applications can be characterized with the proper equipment. The avaiable materials are shown in Table 1. [8]

In addition, to achieve good mechanical properties, metal 3D printing powder must reach the requirements of solid material with high purity, narrow particle size distribution, high degree of sphericity, low oxygen content, good flowability and high loose packing density. The reason for this is the induced porosity during the printing the process is easy to form air gaps, involved and precipitation pores, cracks and other defects; the larger the powder particle size, the more serious the spherification phenomenon.

On the other hand, the smaller the powder size, the higher the surface finish, but the powder flowability will become poor, affecting the uniformity of the powder spread; powder size distribution is too wide, the consistency and uniformity of printing is difficult to ensure; The higher the sphericity of the powder, the better the mobility, the higher the loose density, the higher the density of the sintered parts; the high oxygen content of the powder, the greater the surface activity, the poorer the wettability, the more serious the spherification phenomenon, resulting in a poor melting effect.

Materials in wire form are typically used in DED manufacturing for energy source forms such as E-Beam and laser, which produce denser and higher quality parts. Refractory alloys can also be used in the EBAM process, and with standard deposition rates ranging from 7 to 20 pounds per hour, EBAM works faster than other metal additive manufacturing methods, making it a much more cost-effective way to produce metal parts in a broad sense. Therefore, the raw materials for this wire are higher-priced metals with longer production cycles, and these materials include: Titanium and Titanium alloys, Inconel 718, 625, Tantalum, Tungsten, Niobium, Stainless Steels (300 series), 2319, 4043 Aluminum, 4340 Steel, Zircalloy, 70-30 Copper Nickel, 70-30 Nickel Copper (Table 2).

Powder

Aluminium Alloys	Cobalt Based Alloys	Tool Steels	Copper Alloys	Nickel Based Alloys	Precious Metal Alloys	Titanium Alloys	Stainless Steels
AlSi10Mg	ASTM F75	AISI 420	CC 480 K	Inconel 718	Jewellery Gold	Titanium grande 2	SS 304
AlSi7Mg	CoCrWC	Marage 300		Inconel 713	Silver	Ti6Al4V ELI	SS 316 L
AlSi12		H 13		Inconel 738		TiAl6Nb7	SS 410
		AISI D2		Inconel 7625			SS 440
		AISI A2		Hastelloy X			15-5 PH
		AISI S7					17-4 PH

Table 1

Wire

Aluminium Alloys	Inconel	Tungsten	Copper Alloys	Nickel Bronze Alloys	Chromium	Titanium Alloys	Stainless Steels
5A06	Inconel 718		CuSi3			Ti-45Al	SS 304
AA5183	Inconel 615		AlSi5-ER4043			Ti-55Al	SS316
Al-6.3Cu	Inconel 625		Cu-Al alloy			Ti6Al4A	ER70S
Al-7Si-0.6 Mg							

Table 2

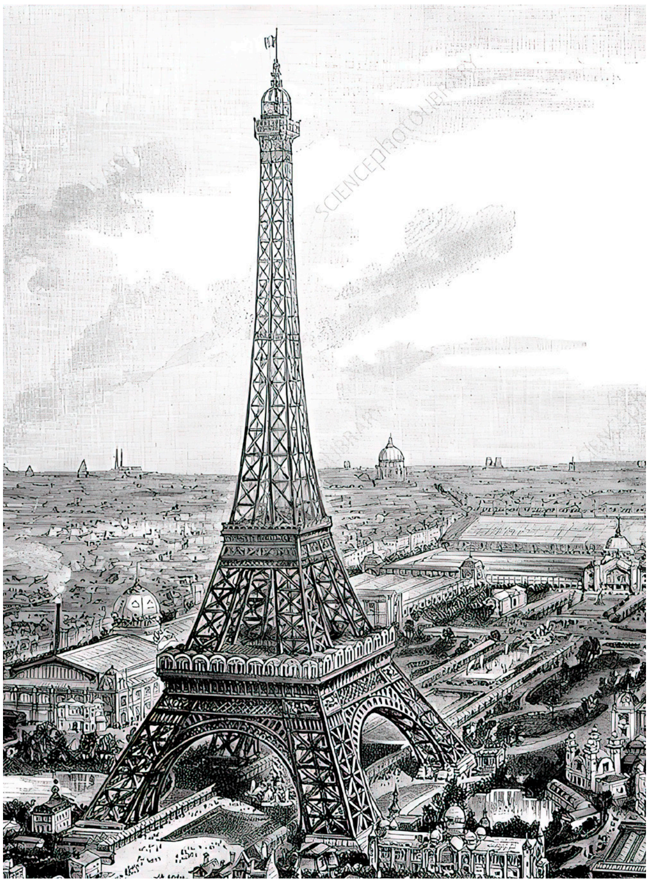
1.4

The history of the metal AM

The history of metal AM is based on the history of the metal itself and the history of plastic AM, and it is because of these two highly developed to a gradual transition to metal AM. The history of metals began earlier than we think, with the earliest the neolithic times, 6000 -3000 BCE, in this period, natural forms of metal such as gold and copper were cold worked into items. The Bronze Age began in 3000 BCE. Copper was alloyed with arsenic or tin and was used in castings and forgings to make strong tools and weapons. After this, the Iron Age began in 1400 -1200 BCE, the Hittites and others began to learn how to forge iron tools and weapons for conquest.

Bronze Age

From the mid-1700s to the late 1800s, important metals such as titanium, tungsten, cobalt, and aluminium was discovered. Importantly, in 1889, World's Fair in Paris, The Eiffel Tower was constructed using 2.5 million rivets. In the late 1800s. The carbon arc process for welding metal was developed. In the 1910s -1950s, building ships and aircraft development of weld processing of steel, aluminium and titanium alloys.
In the 1940s, gas tungsten and gas metal arc welding were invented. In late 1950s, electron beam welding was popularized.



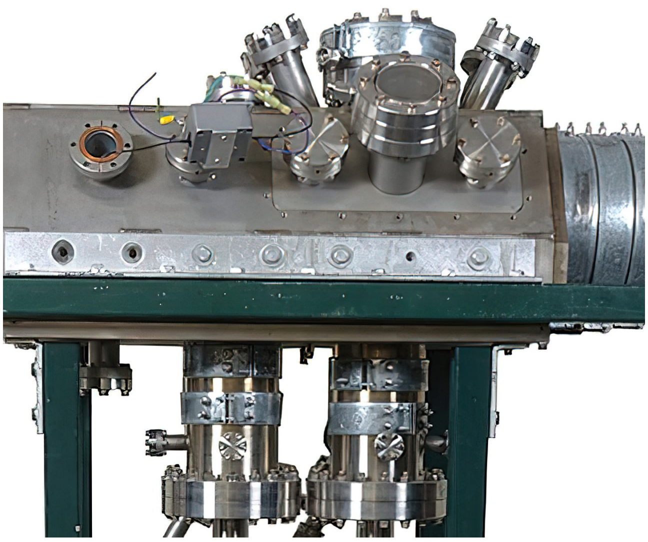
The Eiffel Tower in 1889

There was the development of refractory and reactive metal in 1960, metal was widely used in space and nuclear applications with tantalum, niobium, and zirconium.
In the 1980s and 1990s, the development of AM processes for metal, metal AM had developed magnificently. In the 1980s, the

University of Texas at Austin engineering student Carl Deckard and his advisor Dr Joe Beaman developed and patented a type of additive manufacturing called selective laser sintering (SLS). The first SLS machine, nicknamed Betsy, was completed in 1987. The cube was the first product with a recognizable, complex 3D shape printed by Betsy. In 1983, Charles Hull invented Stereolithography. After a few years, in 1992, DTM CORP (now 3DS) invented a selective laser sintering machine. Immediately after, in 1994, the EOS company, EOS introduced Direct Metal Laser Sintering. In 1994 Arcam invented the Electron Beam Melting (EBM) technology, In 1995, the first Fraunhofer Institute for Laser Technology (ILT) in Germany launched its SLM technology. In 2001, the CONCEPT LASER company introduced Laser Cusing, their AM production system based on SLM.

Time went to 2011 when the Institute of Biomedical Research at the University of Hasselt in Belgium has developed and manufactured a metal mandible, and the metal 3D AM mandible marks the beginning of the clinical application of 3D printed grafts. But the 3D printing industry at the end of 2013 fell into the "trough of disillusionment". In 2016, the famous companies, HP and Canon, Simens entered the AM market. In 2019, metal AM has split into two main categories, inexpensive machines, or machines for mass production.

Carl Deckard and his advisor Dr. Joe Beaman



The first SLS machine

The current status of the metal AM

02

Chapter

2.

The current status of the metal AM

According to the ASTM, AM is a process of joining materials to make parts from a 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.[9]

The main advantage has been shown that traditional subtractive manufacturing requires the extraction of material from more significant parts to form the final 3D imaging process, while the AM process only adds material when needed. It is then combined with material utilization to reduce material waste and its environmental impact.
So far, another major advantage of AM over traditional manufacturing processes is the capability to produce complex designs.
In principle, all products designed using CAD can be produced through add-in manufacturing. In addition, AM can shorten the production cycle without the need for special manufacturing tools, reducing labour time and energy costs.

Many industrial applications of AM have been developed in the last five years. Industrial sectors such as aerospace, automotive and medical are taking advantage of AM and successfully implementing these technologies. Whether it is to replace existing production methods for economic reasons or because of the ability to produce more complex components, it is clear that AM will certainly have an impact on the future of manufacturing. The rapid and significant growth of the AM in the industry is correlated to the more available systems, materials and software on the market. It is estimated that the global value of the industry will exceed $10 billion by 2021. The regional breakdown of metal additive manufacturing machines published in the 2012 Wohlers Report shows that the industry is a truly global one. Governments around the world have identified additive manufacturing as a growth industry and are funding research projects to further, develop the technology. Metal AM offers new possibilities, not only in terms of design but also in terms of material selection. For example, the technology is particularly attractive for processing advanced materials such as titanium, where the cost of conventional processes can be prohibitive. This is also true for many alloys that can only be manufactured at high cooling rates.

AM technology is considered to be the driving force and trigger of the fourth industrial revolution and this may be a misconception. Looking back at the first three industrial revolutions, it is clear that the driving force of industrial production was energy. The first industrial revolution was driven by steam, the second one by the consumption of coal, oil and other non-renewable energy sources to maintain socialized mass production, the third by the automatization of the production.
The energy used in the fourth industrial revolution should be clean, renewable, and not limited by spatial distribution, and the way of transmission should be changed from centralized to distributed sharing ones. The energy we will use in the future is very similar to the current Internet, where the net line of

each terminal in the information the network is widely shared. The energy network is similar in that each home can be equipped with only "generators" that collect renewable energy from nature, such as solar, wind and tidal energy, and convert it into electricity. Perhaps such a vision seems a bit far away, but this is exactly the change brought by the the fourth industrial revolution that is, production must be driven by a change in energy, and it is the third industrial revolution's production methods that 3D printing affects. In this scenario, the development of 3D printing technology has pushed production into diversification and personalization.

General Motors and Autodesk collaborated to redesign a seat bracket

2.1

The development of the AM of metal

Metal AM is not a new thing that appeared overnight, it has experienced a relatively long the process from the germination to the growth and development.

In the 1990s, Laser Directed Energy Deposition (L-DED) technology was developed relatively independently by several international research institutions and was given different names, such as Laser Cladding, Laser Direct Casting, Direct Metal Deposition (DMD), Laser Consolidation (LC), Laser Metal Forming (LMF), Laser Engineered Net Shaping (LENS), Controlled Light Manufacturing (CLM) and Laser Metal Forming (LMF). Laser Consolidation (LC), Laser Metal Forming (LMF), Laser Engineered Net Shaping (LENS), Directed Light Fabrication (DLF), Laser Forming (LF), Laser Babsed Free-form Fabrication (LBFFF), Laser Solid Forming (LSF) and Laser Direct Fabrication (DLF). Directed Laser Fabrication (DLF), et cetera. Although the names of these technologies are different, and the basic technical principles are the same.

DMD technology was first developed in 1996 by Sandia Laboratories in cooperation with Optomec, Inc. in the United States. The process is similar to the DMLS process, except that DMD delivers metal powder through a nozzle, whereas DMLS is processed on a powder bed. The advantages of the DMD process over DMLS are the ability to make much larger parts and the ability to mix different types of metals through the nozzle to create specific metal alloys.

In 1998, Sandia National Laboratories combined the selective laser sintering process SLS with the laser cladding process and proposed Laser Engineered Net Shaping (LENS). From 1990 to the present, the AM technology has realized the forming of metallic materials and entered the stage of direct additive manufacturing, and the electron beam selected zone melting (EBSM), electron beam free-form fabrication (EBF), plasma additive fabrication (IFF), wire arc additive fabrication (WAAM), and other technologies have emerged. Additive Manufacture (WAAM) and a series of other manufacturing processes. At the beginning of the 21st century, research teams have made many efforts and received fruitful results in order to print complex, large and precise parts and to continue to improve the mechanical properties of the parts to achieve practical engineering applications of AM parts.

Metal AM technology with its flexibility, energy saving and environmental protection, adaptable advantages favored by governments, the development of AM in the past 30 years is mind-boggling speed, so far there have been a large number of AM parts commercialization of the case.
Metal AM entered the aerospace field in the 1980s, and by the early 21st century, there were many successful applications. In 2003 Boeing provided 3D printed spare parts for the F-15 fighter jet and began commercial development, and now Boeing has tens of thousands of various types of metal AM aircraft parts. Metal AM technology in

the medical industry has matured, and human implants are a key application area for metal AM. In addition, metal AM has more applications in anatomical models, orthopaedic devices, stents, drug development, and surgical templates. There are fewer reports on the application of metal AM in nuclear power, and the successful The current status of the metal AM 24 installation and safe operation of metal AM chiller end caps at Daya Bay Nuclear Power Station in February 2017 marked the beginning of the engineering application of metal AM in the nuclear power sector.

Industrial AM cases in a wide range of materials

2.2 Applications

-Aerospace and Defense

Aerospace technology requires innovation and the boost of 3D printing technology. Laser forming technology for high performance metal components used on spacecraft are a technology that uses alloy powder as the raw material to create "near-final shape" high performance large components in one step directly from the part molds through laser melting and layer-by-layer deposition.

Consolidation from the number of parts directly manufactured in one step from the mold "near the end of the shape" high-performance large components of the technology were rapidly developed from the first proposed by the United States in 1992. Because the laser forming technology of high-performance metal components have outstanding advantages for the short-cycle, low-cost forming and manufacturing of large titanium alloy high-performance structural parts, it has a broad application prospect in the development and production of aerospace equipment, and is highly concerned by the the aerospace industry of various countries. 3D printing laser rapid forming advanced technology does not require large and super-large forging equipment, forging die; high material utilization, digital control processing time, short production cycle; low manufacturing cost, with "ultra-fast response" and "on-site rapid repair" capability. [10]

Combined with the existing technical achievements and the characteristics of

3D printed GE9X TiAl alloy blade

aero-engine parts, the application of AM technologies in aero-engine is mainly used in the following aspects:

(1) parts that are difficult to manufacture by traditional processes;

(2) long production preparation parts, reducing manufacturing costs by reducing tooling and shortening manufacturing cycles;

(3) high-cost material parts, improving material utilization to reduce raw material costs;

(4) high-cost engine parts repair;

(5) combined with topology optimization to achieve weight reduction as well as improve performance (cooling performance, et cetera);

(6) integral design parts to increase product reliability;

(7) manufacturing of heterogeneous materials;

(8) rapid concept response during engine development;

(9) printing resin models for engine simulation assembly, et cetera.

General Electric (GE), one of the world's leading aero-engine companies is focused on developing selective laser melting (SLM) and electron beam selective melting (EBM) technologies for aero-engine parts. Among them, SLM-shaped fuel nozzles have made the most significant progress and are now used in the first flight of the LAEP-X engine developed by CFM International.

Compared to traditional forged + machined + welded fuel, the AM fuel nozzle reduces the need to weld and assemble a large number of parts while designing a more complex internal structure to improve component performance. This study was named one of the world's top 10 technological breakthroughs in 2013, with a maturity level of TRL>8 and FAA airworthiness certification. [11][12]

TiAl intermetallic compounds have low density, high specific strength, high melting point and high temperature, and are considered to be a new type of lightweight, high-temperature structural material that can replace nickel-based high-temperature alloys. TiAl-based alloys are mostly made by ingot metallurgy and precision casting. TiAl-based alloys are mostly formed by ingot metallurgy, precision casting, and hot isostatic pressing. TiAlbased alloy components can be sintered in a single process and can avoid the problems associated with casting and hot isostatic pressing. The EBM process allows for the sintering of complex parts in a single pass and avoids the problems associated with casting and hot isostatic pressing.

Powder materials are currently the most commonly used materials for metal-based AM technology. Moreover, the metal powder's quality significantly affects the final product's

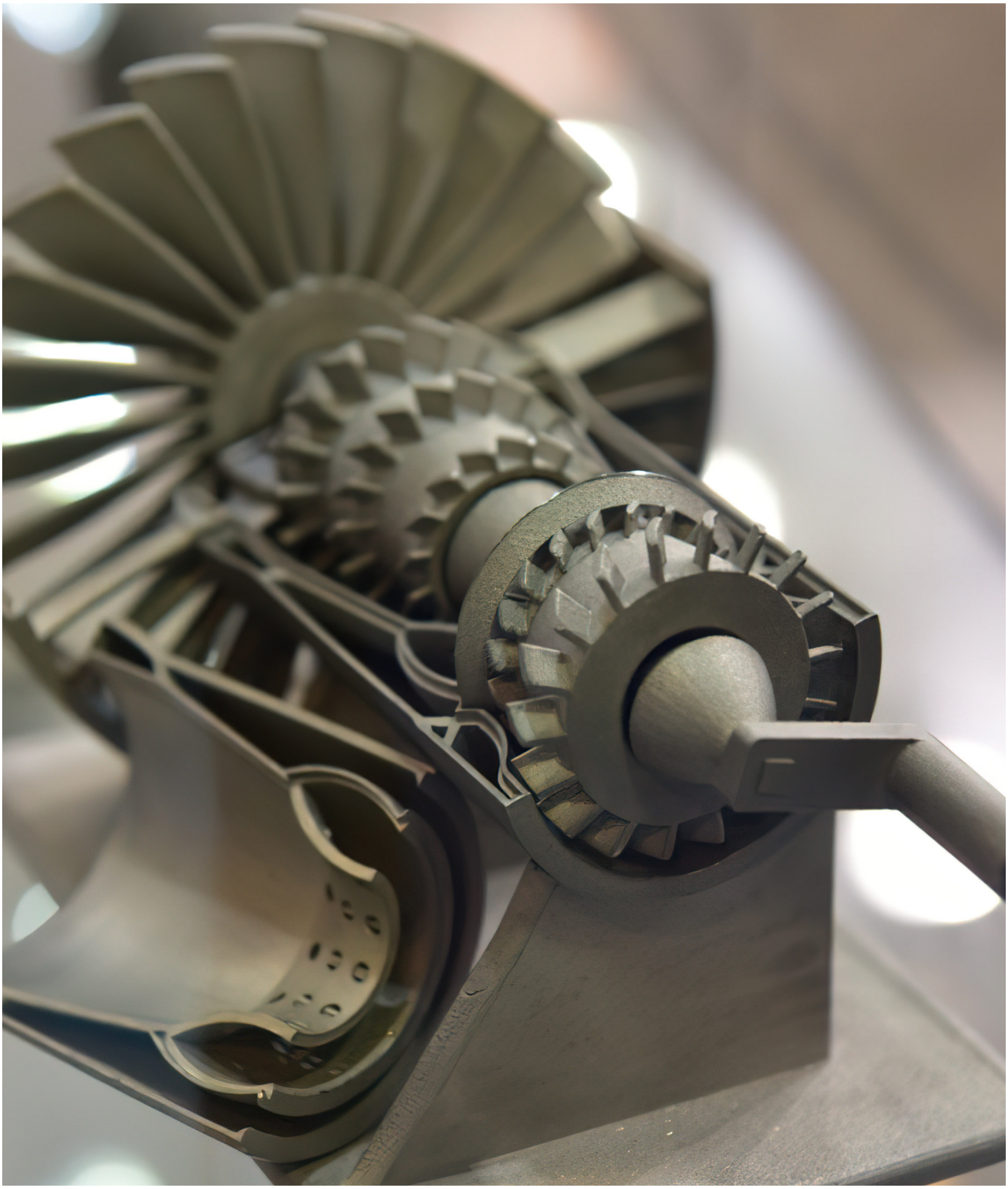
GE LEAP Fuel Nozzle

quality. Studies have shown that not all metal powders are suitable for AM. Some powders are susceptible to spheroidisation, voids, cracks and other defects under the corresponding thermodynamic and kinetic laws. Therefore, analytical tests are needed to determine the compatibility of aero-engine component materials with various additive manufacturing technologies.[13]

The production difficulties of AM for metallic materials are: melting point of metals, forming process involves solid-liquid phase change, surface diffusion and heat conduction, and rapid heating and cooling of the melt pool. The rapid heating and cooling processes of laser or electron beam are likely to cause large residual stresses inside the parts. The requirements of engine parts in terms of manufacturing accuracy and performance are often higher then those of conventional parts, such as dimensional accuracy, surface roughness and mechanical properties. The current AM technology cannot fully meet the accuracy and performance requirements of engine parts in many indexes, and requires post-forming treatment or postprocessing. To realize the application of AM parts in engines, many key process technology issues still need to be solved to achieve effective control of metallurgical quality and mechanical properties of the parts.

A Stainless Steel 3D printed mold

3D printed injection head for rocket nozzles designed by ArianeGroup



Titanium 3D printed parts

-Automotive

In early 2013, the world's first 3D-printed car, the Urbee 2, was introduced as a three-wheeled hybrid car with the majority of its parts 3D printed. The Urbee 2 relies on AM technology to "print" the shell and parts, and the researchers' main work included assembly and commissioning, a process that took roughly 2,500 hours. A video released shows that the car has three wheels, except for the engine and chassis, is metal, using traditional processes to produce, the rest of the material is mostly plastic, the the entire car weighs 1,200 pounds.

In modern industrial conditions, machine a part or make a model, a mold needs to be made first. The cost of making this mold is very high, and it is not worth it until a certain volume is available. Alternatively, a CNC machine can be used to remove the unnecessary material directly from the blank material, but this method wastes a lot of material and is very slow if compared with sand casting. In addition, both of these are very difficult to process for parts with particularly complex shapes and high accuracy requirements, and the processing time required can be very long. 3D printing can make the manufacturing process simpler to make complex-shaped objects quickly and accurately. This is the most significant advantage of 3D printing. According to these advantages, we could predict the manufacture and research of automotive field.

Redesign of car structure: the development of electric cars, replacing the traditional engine, the entire car structure will be significantly changed, when the motor will be installed in the wheel hub, connected by wires to the battery, the traditional engine system and transmission system, et cetera. are no longer needed, replaced by on-board communications, and audio and video systems. There are many parts that can be manufactured by AM. Automotive lightweight can be achieved not only from the use of proper materials, but also from the design of complex components to achieve weight reduction. Private customization. Under the premise of safeguarding the necessary functions, the car's appearance and individual needs are loved by consumers and are also a beneficial weapon to compete in the market, so private customization is also one of the key directions of concern for car manufacturing.

Therefore, the metal AM advantages in automotive manufacturing production can be divided into four main areas:

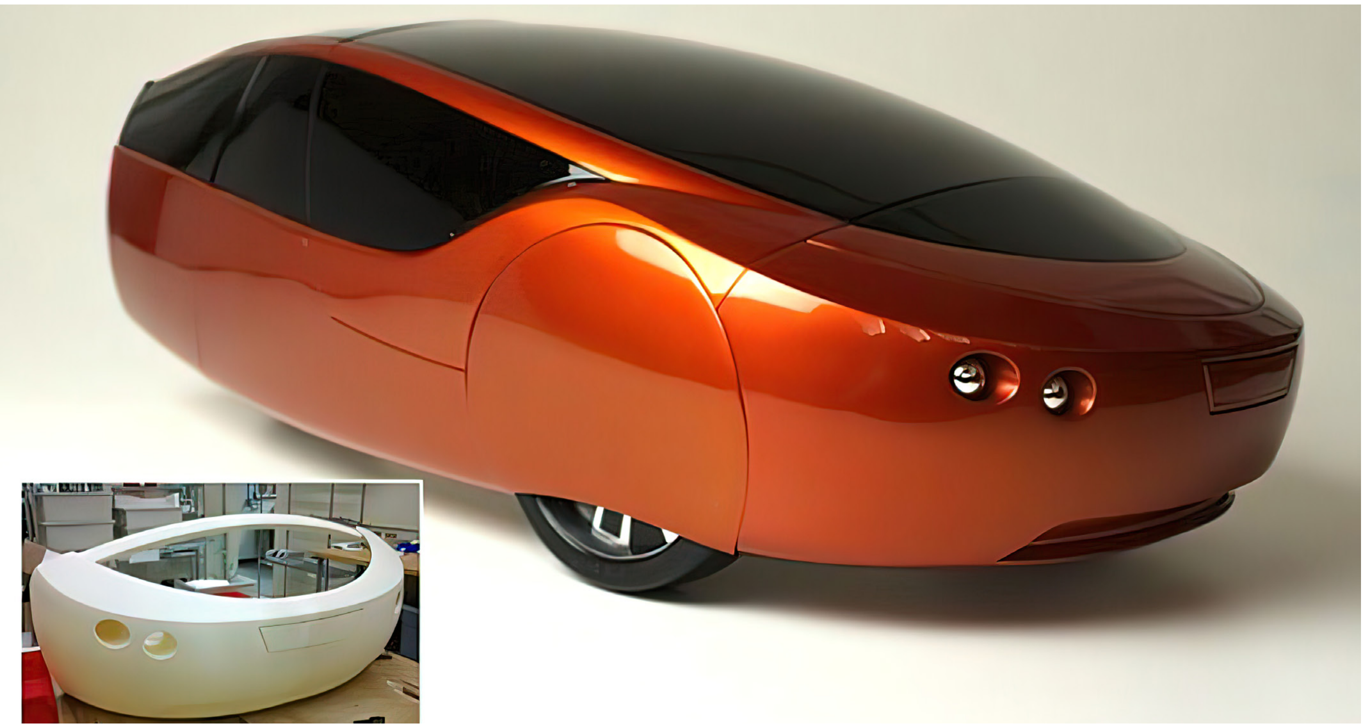
(1) reduce the research and development cycle, reduce research and development costs by exploiting AM to produce trials.

(2) automotive lightweight;

(3) personalized design;

(4) parts supply.[14]

FUV Automotive 3D Printed Steering Knuckles(left), the original component is a nine-piece weldment weighing about 6 pounds (right)



Urbee 2

World's first 3D printed eight-piston caliper


3D printing fixes car door handles--BMW507

-Industrial and manufacturing

As we all know, the traditional machinery manufacturing production must go through many processes such as design, mold, molding and pouring, the manufacturing process is extremely complex. If some small and complex castings are made, the yield is also relatively low. Generally speaking, the yield is often only 20-30%. The application of 3D printing technology in machinery manufacturing can significantly increase the yield of machinery manufacturing, with some machinery manufacturing yield reaching 100.0%.[15]

Mold inserts can benefit from complex conformal cooling channels to speed the molding process and improve part quality.The use of metal AM allows for the fabrication of complex cooling channels with high durability, leading to significant productivity gains. Applications such as these place additional reliance on the computer-aided engineering analysis of potential designs to fully optimize the benefit of AM processing. In addition to conformal cooling, AM metal processing may be used to repair or modify existing tooling to extend the life or increase the performance of existing parts.[16]

The use of 3D printing technology to improve the machine manufacturing yield is still far from enough to ensure the quality of the product on this basis. This 3D printing technology is also fully capable of doing. In the process of printing mechanical parts products, the materials used include aluminium, cobalt, chromium, copper, stainless steel, titanium and the printed mechanical parts are dense sintered metal, which not only has higher strength and hardness, but also has strong flexibility. In short, 3D printing technology can ensure the quality of mechanical parts.[17] Print time will be a breakthrough in the field of machinery, in the premise of ensuring quality, and improve the speed will allow metal additive manufacturing in mechanical products are widely accepted.

Metal AM production tool and mold components

-Medical and Dental

Medical metals, mainly include precious metals, titanium, tantalum, niobium, zirconium and other metals, and stainless steel, cobalt-based alloys, titanium alloys, nickel-titanium shape memory alloy magnetic alloys. Medical metal materials that have been used in clinical materials are mainly stainless steel, cobalt-based alloys, and titanium-based alloys. Titanium and titanium alloys are non-toxic, lightweight, strong, and have excellent biocompatibility, making them ideal medical metal materials. [18] Metal medical implants, as certifications for medical use are being approved for human use in the European Union (EU) and the US. Over 50,000 medical devices have been implanted for the medical industry as produced by the electron beam melting (EBM) AM process alone. [19]

Clinical The basic requirements for surgical metal implants are:
(1) materials with small toxic and side effects, non carcinogenic, non-mutagenic and non-tissue reactive;
(2) strength and fatigue resistance;
(3) stable chemical properties (corrosion-resistant);
(4) good compatibility with human tissue, does not cause poisoning and allergy and other reaction.[20]

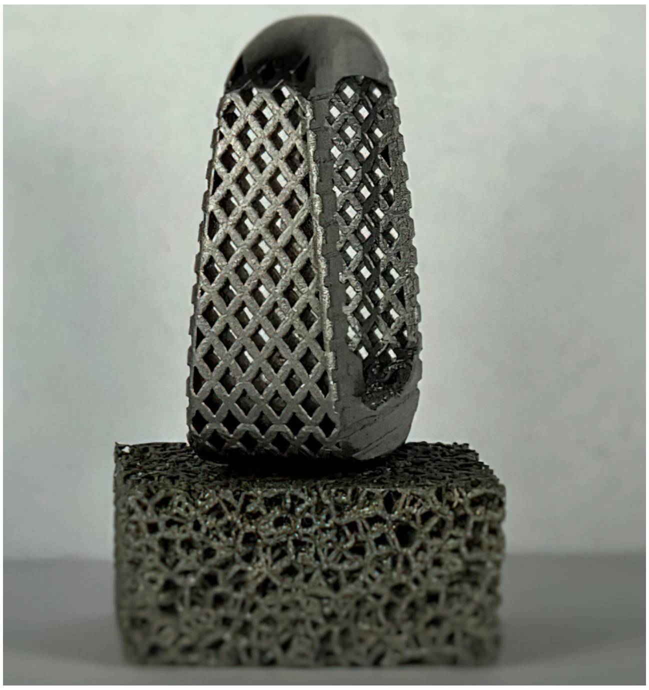
With the increasing maturity of 3D metal printing technology, 3D metal printing in the field of dentistry will be more and more widely used oral and maxillofacial surgery, oral prosthetics, oral implants, orthodontics facial surgery, oral prosthetics, oral implants, orthodontics and other specialities. In particular, with computer-aided design technology, individualized restorations can be prepared according to the different conditions of each patient. The use of this technology is becoming more and more widespread. It is reported that the application of SLM technology: the production of cobalt-chromium metal base crown gold - porcelain bonding force is comparable to the traditional process.[21]

-Software and Services

To enjoy the true benefits of 3D printing, designers must take full advantage of 3D printing's design freedom, part integration, and rapid customization capabilities. Without integrating and implementing these capabilities, metal 3D printing design software may never be viable.

Today, build preparation software solutions are not only evolving rapidly but are helping to achieve consistent and improved output, resulting in faster print times, better surface finishes, and increased strength of printed parts. These software suites now also merge data and machine learning to predict better parameters so they can be implemented in 3D printers. As technology evolves, the software will only get better to increase manufacturing possibilities.

Cobalt-chromium alloy metal powder suitable for biomedical applications.



Tangible Solutions, 3D printed titanium implants.

3D printed rib prosthesis from Renishaw

-On Demand Consumer Personalized Mobile

The main application areas of 3D printing for personalized design are in medical, such as surgery, orthopedic surgery, car customization, custom bicycles, et cetera. For example, in the field of dentistry, oral and maxillofacial surgery, restorative dentistry, oral implants and orthodontics are actively researching in this area, especially with computer-aided design technology, individualized restorations can be prepared according to the different conditions of each patient. The restorations can be prepared according to the different conditions of each patient. Restorative dentistry: scholars are working on the application of 3D printing technology to prepare metal crowns, bridges, and removable partial denture brackets. It has been reported that the application of with SLM technology: the gold-ceramic bonding of cobalt-chromium metal base crowns are comparable to that of the traditional process. The strength of the crown is comparable to the conventional process. [22]

In orthopedic medicine, metal AM personalization is of great help to bone tumor patients. For bone tumor patients, especially malignant bone tumor patients, an important the issue is the reconstruction of bone defects after tumor resection, and both autologous bone grafting, as well as tumor inactivation reimplantation and allogeneic bone grafting have their problems. However, 3d printing technology provides them with a new option to reprint the bone defect using printing technology in the design of the prosthesis.

In the process of prosthesis design and manufacturing, the shape, strength, firmness, and the weight of the prosthesis should be taken into consideration depending on the patient's condition, and the surface of the prosthesis should be designed accordingly according to the different tissues it contacts. [23] In automotive design, personalized customization to meet the consumer's desire for private customization is a selfish in vain amplification and vanity, but metal AM makes this high-end customization requirements become civilized.

During the design and production of a car, the designer has to consider ergonomics to set car seat height, dashboard arrangement, mirror size, et cetera. Ergonomics is based on most of the ergonomics is based on most of the customer's data to measure and count the data, and select the best design solution, which cannot take into account. It is not possible to take into account the needs of each customer. Each customer buys a car that is mass-produced from the production line. There is no personalization, and they can only passively accept the shape and the configuration that they do not like or are not suitable. They can only accept passively. If the customer asks for personalization under the traditional production method, he or she will pay, and the economic cost is extremely high.

To mass production of auto parts in the most representative wheel hubs, for example, if the manufacturer attempts to use AM technology to produce the same brand and shape as the traditional factory tires, 3D printing, small-batch production caused by higher costs, and longer production cycle will undoubtedly make it difficult for enterprises to have long-term development, or even to extinction. However, if companies switch their business model from mass production to mass production, their target customer the base will shift to those who are willing to spend more money on custom wheel design services to meet their different consumer psychology. [24]

-Remanufacture and Repair

3D printing technology can be used for the restoration and molding of used and high value-added high-tech products. A

Titanium hip-implant 3D printed by Protolabs.

wide variety of AM equipment is available, depending on the use of the workpiece being processed working conditions, material characteristics and production technology.

The most suitable treatment technology is selected to improve the wear and corrosion resistance, oxidation and thermal corrosion resistance of metal surfaces, repair the service damage and manufacturing defects of metal materials, and realize the reliable connection of hard-to-fuse, hard-to-weld and easily deformed metal components.

The use of AM technology can not only quickly realize the new product "from nothing", but also quickly realize the waste product "bad in the repair" and improve its performance, extend its service life, which has a very important economic significance. 3D printing remanufacturing is the use of 3D printing technology to remanufacture of old parts to improve their performance and extended their service life. As can be seen from the table 3, the acquisition the remanufactured repair model is a complex process. First, it is necessary to obtain the digital model of the used and damaged parts through inverse engineering, and then process the digital model and finally generate the remanufactured repair model by comparing it with the standard model. Because the factors that cause damage to equipment parts can be varied, the part damage surface is often irregular, to achieve in-situ repair of the damaged part of the part.

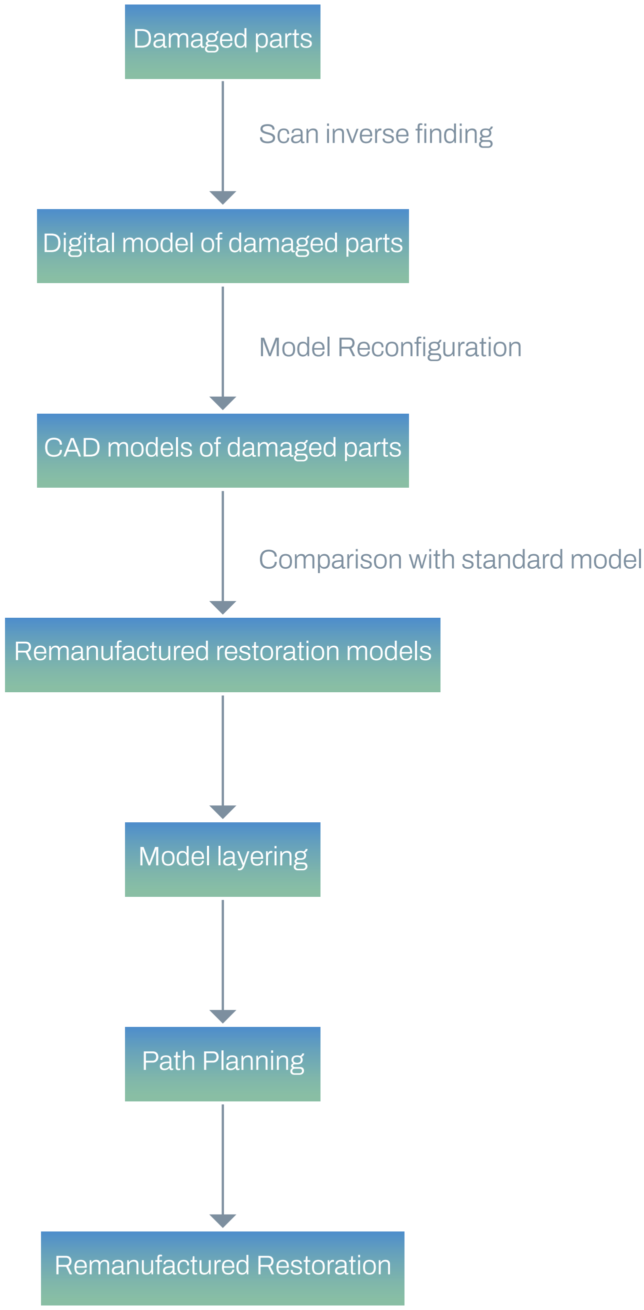


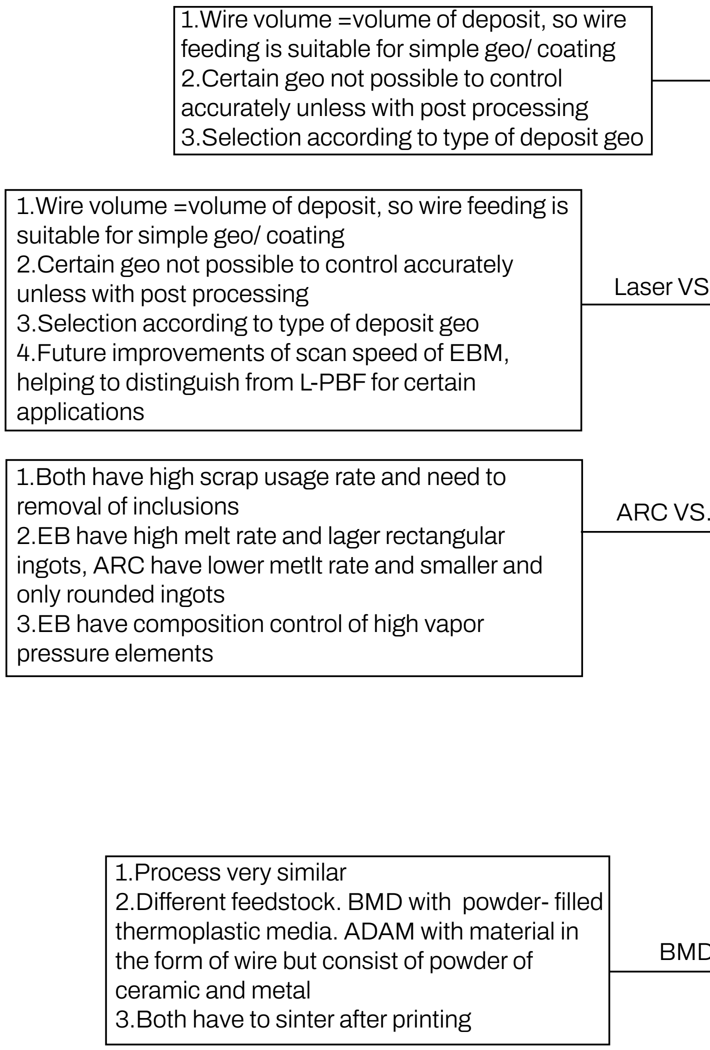
Table 3

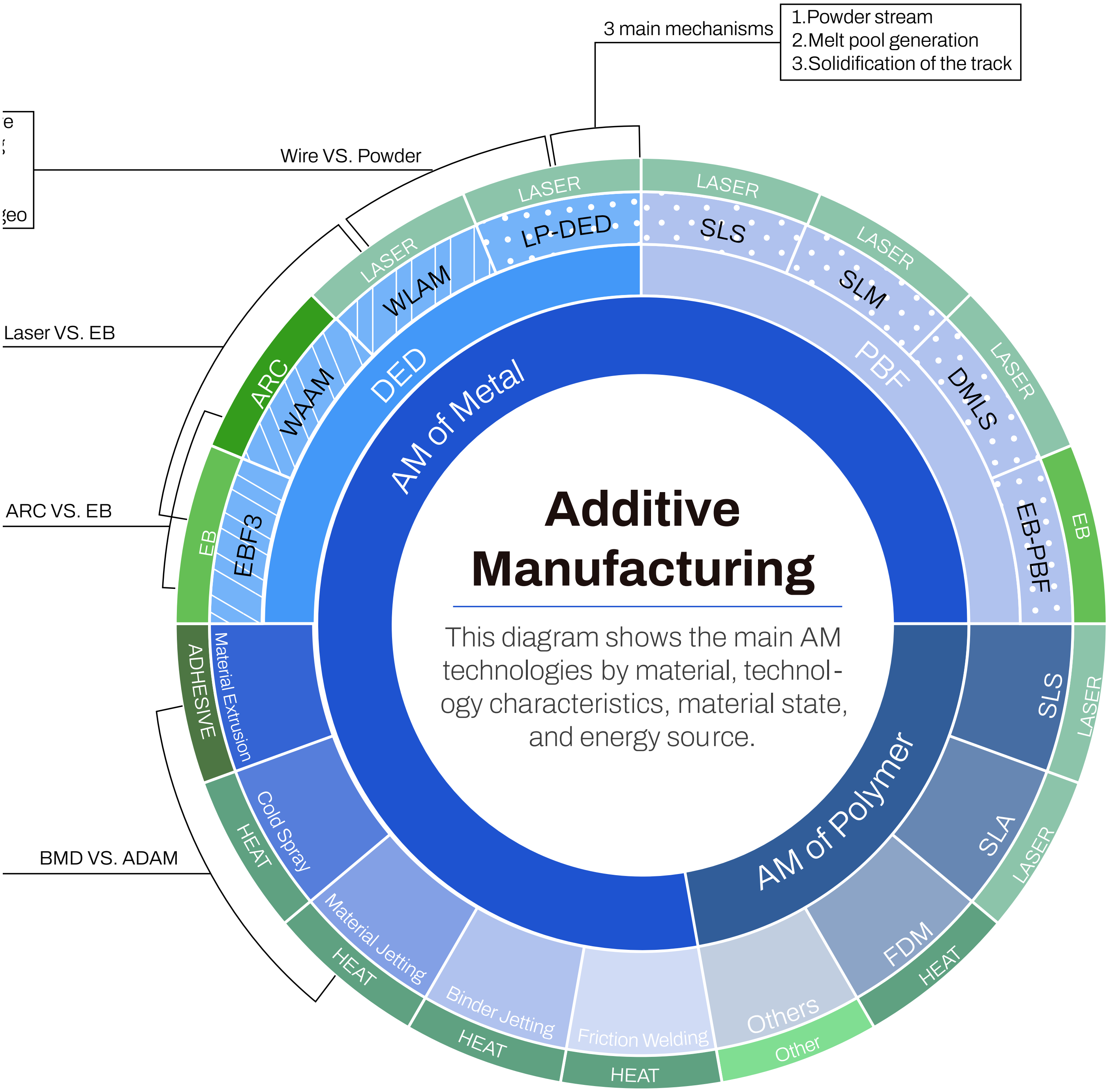
A damaged surface pre-treatment can also be considered. In-situ repair, the damaged surface must also be pretreated. In addition, due to the remanufacturing repair process in the damaged parts, the remanufactured repair materials used and the parts base material is different, remanufactured repair parts in the problem of the heterogeneous interface. Therefore, the 3D printing remanufacturing repair of equipment, scrap damaged parts is different from the 3D printing, direct manufacturing of equipment parts, which involves a broader technical field and a more complex process. Take the high-performance aero-engineintegral leaf disc, for example, its manufacturing cost is very high; a single value of 60 ~ 75,730 USD, but it is very low in the manufacturing process yield, the blade is prone to cracks, trachoma and other defects, through metal 3D printing technology to restore the defective parts, not only can make the damaged parts to restore the shape and size, but also make its performance reach or even exceed the level of new products, which can significantly improve the production efficiency and reduce production costs.[25]

The iconic VW minivans were all restored using 3D printed car parts.

2.3
The categories of the AM of metal

AM metal classification can be divided into three main categories from materials state: wire, powder and other, where DED and PBF, powder and binder are the three main technical classifications that have been included in it. Specifically, most of the DED materials are wire; under this general classification, according to the different energy sources can be divided into E-BEAM, Arc and laser. A. DED can work for polymers, ceramics, and metal matrix composites. It is predominantly used for metal powders. While the materials of PBF are all metal powders, there are only two types of energy sources, laser and E-beam. Other classifications can be seen in the figure.




3 main mechanisms
1.Powder stream
2.Melt pool generation
3.Solidification of the track
Wire VS. Powder
Laser VS. EB
ARC VS. EB
BMD VS. ADAM
Additive Manufacturing
This diagram shows the main AM technologies by material, technology characteristics, material state, and energy source.
AM of Metal
AM of Polymer
DED
PBF
LP-DED
WLAM
WAAM
EBF3
SLS
SLM
DMLS
EB-PBF
LASER
ARC
EB
Material Extrusion
Cold Spray
Material Jetting
Binder Jetting
Friction Welding
Others
FDM
SLA
ADHESIVE
HEAT
Other

2.4
PBF

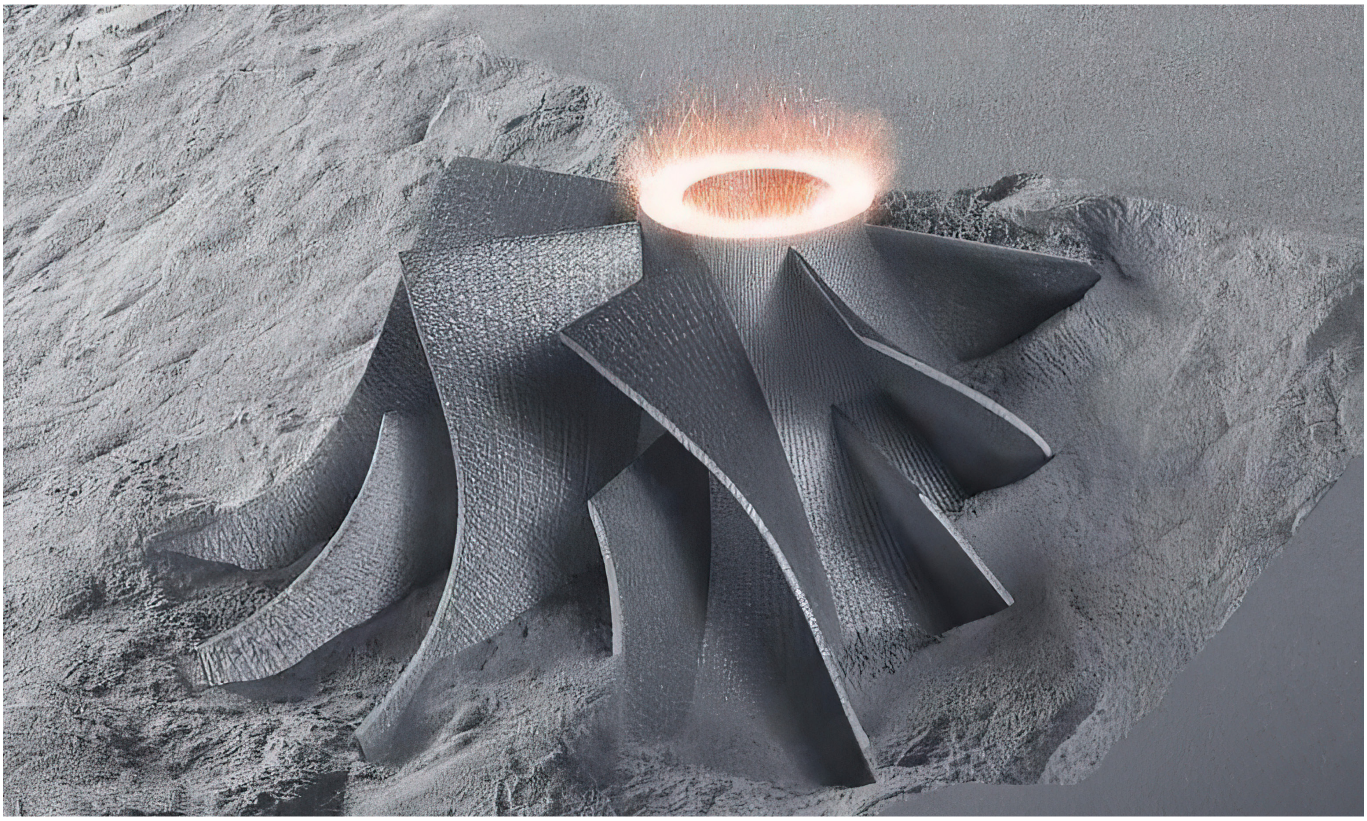
PBF is AM process in which thermal energy selectively fusesregions of a powder bed. [26] PBF materials are metal powders, classified from energy sources such as laser and E-beam.

Laser Powder Bed Fusion (L-PBF) with laser as an energy source. The other names as this technology is also known are: Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS). Laser powder bed fusion (L-PBF) metal AM technology iscurrently well studied in both industry and academia as it offers the best reproducibility and dimensional accuracy for part production.

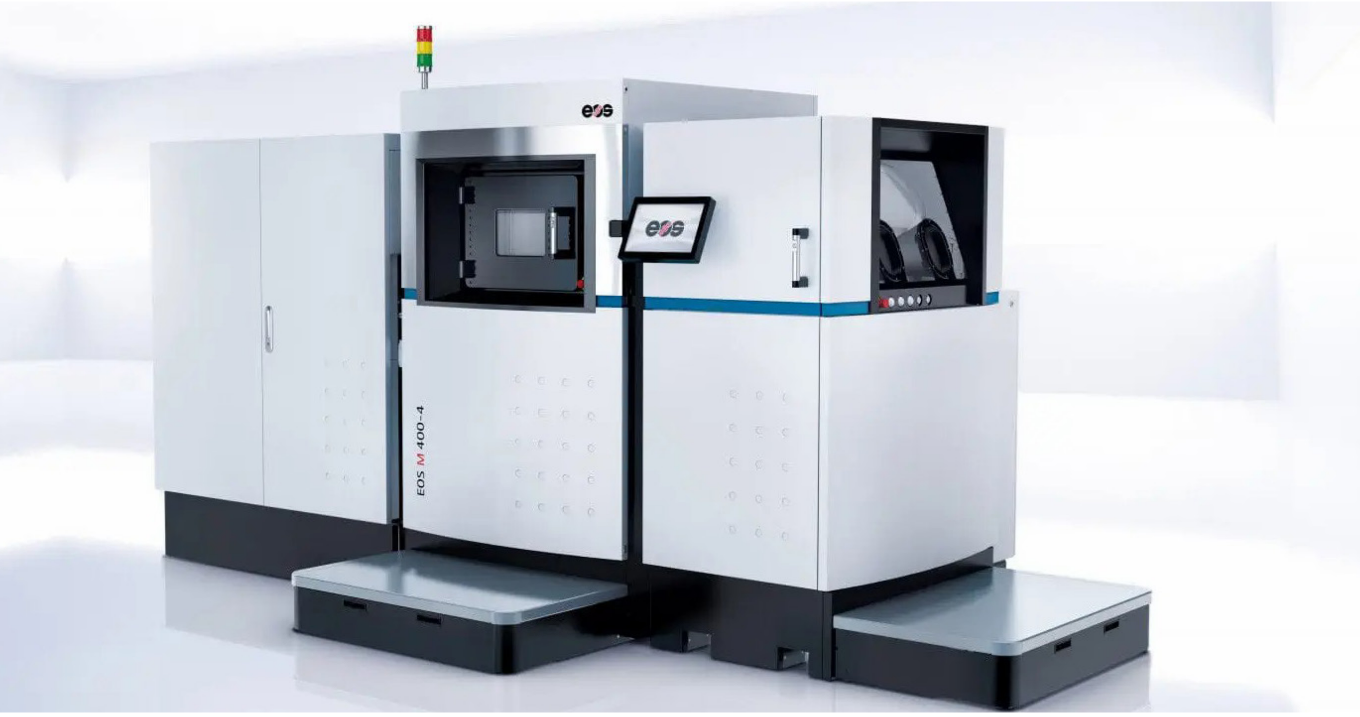
The founding patent for L-PBF originates from the Fraunhofer Institute's laser research Kurt invented the facility in Germany and Wissenbach and Andres Gasser, and WilhelmMeiners. Initially, the technology was not well received, but thanks to the persistence of the three, L-PBF technology is now widely used in industrial applications and dominates the metal AM technology, reportedly accounting for more than 80% of the market. From turbo machinery to aerospace and medical technology, it accounts for a global market, including systems, materials and services sales of around €2 billion. Since L-PBF metal 3Dprinting technology builds components layer by layer, it is a 3D manufacturing technology-based on 2D manufacturing, which offers many system advantages over traditional manufacturing techniques, such as the ability to generate complex cooling channels for lightweight structural (e.g. Dot matrix structure) applications, achieve more complex micro structures, et cetera. Another advantage is the reduced development time, which allows for more straightforward implementation of multiple design iterations, which can shorten the time to market for new products.

In general, the L-PBF technique uses the following steps to fabricate components:
(1) a layer of metal powder of specified thickness is spread on a build plate inside the machine;
(2) a laser beam is used to selectively melt the desired area within the layer;
(3) the build plate is moved down and a new layer of powder is spread on the build plate. This process is repeated layer by layer until the part is manufactured. The positive process results of the LPBF metal AM build are controlled by various process parameters including, but not limited to, beam power (P),scanning speed (V), hatch spacing (H), layer thickness (D), and scanning mode, among many others. The SLM system consists of a laser, a scanning system, a powder roller, a powder bed and a powder conveying system.

As L-PBF is an AM technology,selective laser sintering (SLS) adopts liquid-phase sintering mechanism. During the forming process, the laser partially melts the powder material, and the powder particles retain their solid-phase morphology. The powder densification is realized through subsequent liquid-phase solidification, solid-phase particle



PBF technology



L-PBF machine, EOS M 400

rearrangement and bonding. The SLS system consists of a laser, a scanning system, a powder roller, a powder bed and a powder conveying system.

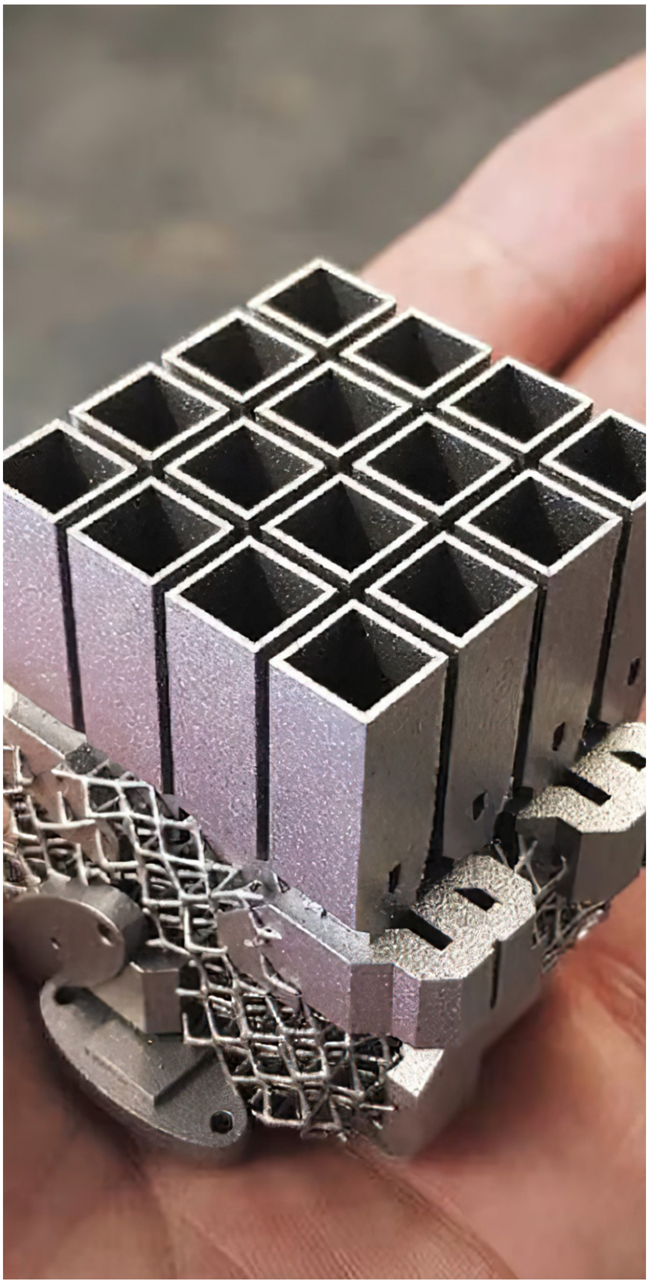
Before sintering begins, the metal powder is preheated to a temperature lower than the sintering point, the powder supply cylinder on one side rises to a given amount and the powder laying roller spreads the powder evenly onthe surface of the powder bed, and the laser beam, under the control of the computer system scans the cross-sectional profile of the first layer according to the set power and speed. After the laser beam has been scanned, the powder is sintered into a solid contour layer of a given thickness, with the unsintered powder serving as a support, thus completing the sintering of the first layer of the part. At this point, the powder bed is shifted down a layered thickness, the powder supply is shifted up, the powder roller is repowered,the laser beam is sintered in the next layer, and the front and rear sintered solid layers are naturally bonded as one, and so on, layer

Removing a DMLS print from the powder.

by layer, until the 3D solid part is sintered.

Selective Laser Melting (SLM) is a rapid forming technology developed on top of SLS. Before the laser beam scanning begins, a thin layer of metal powder is evenly spread on the platform using a powder spreading blade, and the laser the beam is computer-controlled to selectively laser melt the current layer; after the melted metal powder cools and cures; the platform is lowered by one unit height and the powder supplier is raised by one unit height,the powder spreading roller re-lays the metal powder on top of the processed layer, and the laser beam begins to scan a new layer, and so on. The whole process of SLM is carried out in an inert gas-protected chamber to avoid oxidation of the metal at high temperatures.From the above two introductions, we can easily know that although the principle of both technologies are to use the thermal effect of the laser beam, the laser used in SLS and SLM is different due to the different objects of laser action. For SLM technology, a laser beam with a higher absorption rate of the metal is used, so shorter wavelengths such as Nd-YAG lasers (1.064 microns) and fiber lasers (1.09 microns) are generally used. The the main difference between SLM and SLS is that SLS does not entirely melt the metal powder, while SLM completely melts the metal powder and forms it.The utilization rate is very high, and the subsequent treatment the process is eliminated. However, SLM also has some drawbacks, such as expensiveSLM equipment, low manufacturing speed complex process parameters, and the need for additional support structures.

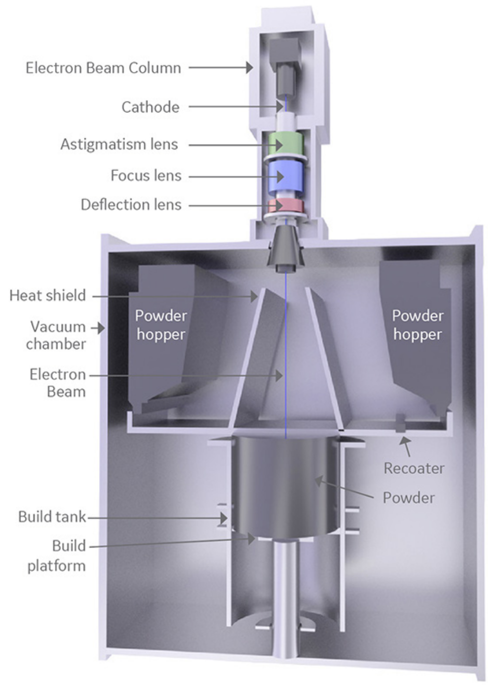
SLM is a process that uses a high-energy laser beam(200 W) to directly sinter thin layers of metal powder (20-60 μm) to form dense solid parts based on 3D model data. SLM is essentiallythe same principle as SLS;



A satellite antenna produced through DMLS the main difference is the powder. The parts produced through SLM have better material structure/mechanical properties than parts produced by conventional techniques and can be used to build objects from almostany metal alloy. After printing, the object slowly cools, and the excess powder can be recovered from the build chamber and recycled.

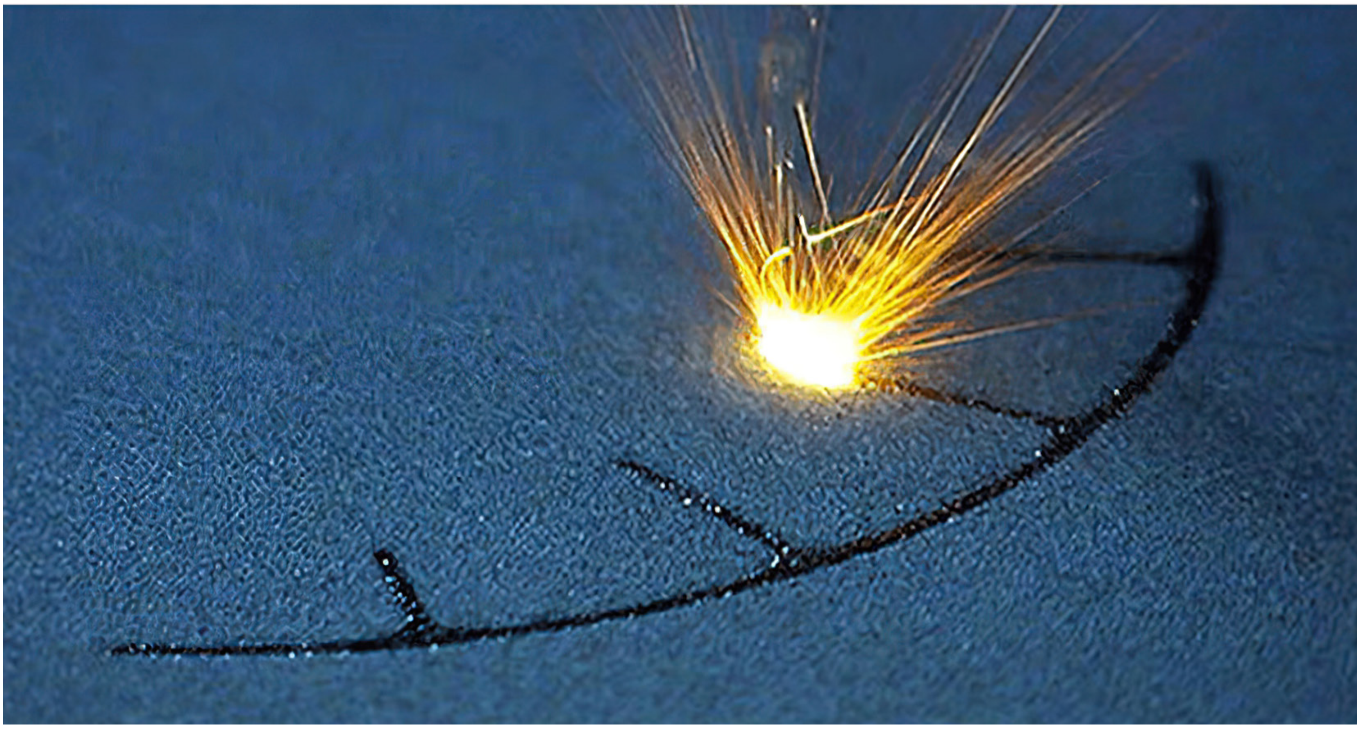
EB-PBF is an AM technology that uses an electron beam to irradiate and melt metal powders. First, a thin layer of metal powder is laid on the substrate and the powder layer is heated by electron beam irradiation of the entire powder layer. The wide range of scanning irradiation of the electron beam heats the powder to the desired temperature. After the powder is preheated, the electron beam is deflected by an electromagnetic field that feeds energy into the powder layer, which continues to heat the powder above its melting point and selectively fuses the powder layer. Afterwards, the forming platform is lowered, and a new layer of powder is spread on the platform. Continuous layer-by-layer heating and the selective fusing of the powder layers results in a final stacking to form a shape consistent with the 3D model.

The basic structure of the EB-PBF machine consists of an electron beam gun, an electromagnetic coil to guide the electron beam to the desired shape for scanning,and a vacuum chamber with a powder spreading mechanism inside. Typically, the electron beam has a maximum power of 3-6 kW . The electrons are emitted from a heated filament or crystal and accelerated by a high voltage. The electromagnetic coil positions the electron beam in a process similar to the optical lens's focusing and positioning of a laser beam. During the forming process, the forming chamber and the electron beam gun are always under vacuum.It takes about one hour to prepare the required vacuum environment. After forming,the chamber is filled with inert helium gas to speed up the cooling process. Cooling in helium for several hours is required before the forming chamber can be opened and safely exposed to air without powder oxidation.



Schematic sketch of a PBF-EB system (GE)

LPBF's Solukon powder remover automatically removes loose powder from finished parts



A laser selectively melting powdered metal inside a laser powder bed fusion 3D printer from GE Additive

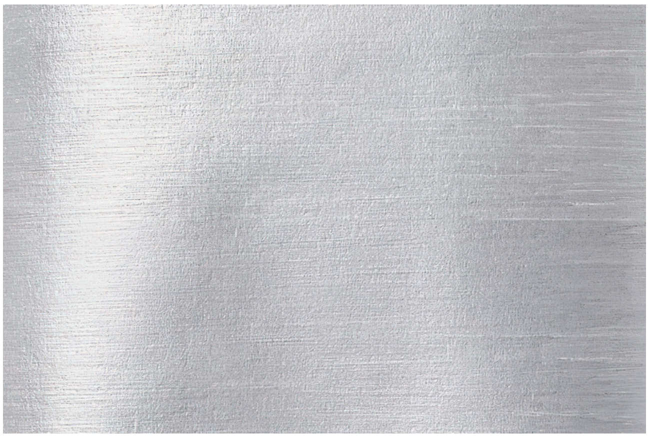
2.4.1
PBF material

Common engineering alloys based upon steel, nickel, titanium, cobalt chrome molybdenum (CoCrMo), metal matrix composite materials and other special metals are used in L-PBF.

SLS and SLM are both based on the thermal effect of the laser beam, but the laser used in SLS and SLM are different because the target of the laser is different, and the co2 laser with a longer wavelength (9.2-10.8 microns) is used in SLS. Therefore, shorter wavelengths such as Nd-YAG lasers (1.064 microns) and fiber lasers (1.09 microns) are generally used. From the material point of view, there is a big difference between the two technologies; SLS technology uses materials other than the main metal powder, but also needs to add a certain percentage of binder powder, the binder powder is generally a low melting point of metal powder or organic resin. SLM technology because it can make the material completely melted, so the general use of pure metal powder. Since the powder of SLS technology is mixed powder, even if the metal powder is used as the binder, the strength of low melting point metal material is generally lower, so the strength of the sintered parts of SLS technology is lower compared with the parts of single metal material.

The EB-PBF, like the PBF-LB, requires a spherical powder due to the limitations of the available powder lay-up technology. Due to the configuration of commercially available machines, we usually see a rougher surface finish on EB-PBF parts, and they are currently mainly used for printing titanium alloys. EBM

Nickel alloys



Aluminium alloys

Cobalt chrome alloys

Q10plus, Arcam EBM Q20plusand other machines can manage Ti6Al4V, Ti6Al4V ELI, Titanium Grade 2 (ASTMF75), Cobalt-Chrome, and Inconel alloys.

EOS M 290

2.4.2

Advantages and disadvantages of PBF

PBF technologies have the advantage of direct fabrication of complex structured metal products and short fabrication time, extensive use of materials, low price, high material utilization, relatively simple manufacturing process, design and manufacturing integration, and a wide range of applications. In addition, the process does not require the design of support structures, and the un-sintered powder directly supports the overhanging part of the forming process, and the forming accuracy can reach 0.05-2.5 mm on average, which can realize a certain amount of personalization. However, the PBF process also has many shortcomings: high cost of raw materials and equipment; loose and porous parts inside, large surface roughness and maximum size of parts is limited.

The advantages of SLM are: the densities of metal parts are more than 99%, and the excellent mechanical properties are comparable to forging; the powder is completely melted, so the dimensional accuracy is very high (up to ±0.1 mm), and the surface roughness is good (Ra is around 20-50μm); the selection of materials is extensive, the utilization rate is very high, and the subsequent treatment process is eliminated. However, SLM has some drawbacks, such as expensive SLM equipment, low manufacturing speed, complex process parameters, and support structures. The most significant advantage of the SLM process is that it does not require expensive and time-consuming pre-treatment and post-treatment processes and it can be used for small batch production due to its high production accuracy (±0.05 mm) and the fact that the overall density of the part is more than 90% of the theoretical density. However, the "spheroidization" effect and sintering deformation of metal powders in SLM make it difficult to shape complex metal parts accurately. On the other hand, EBM technology has the advantages of fast forming speed, no reflection, high energy utilization, non-polluting processing in a vacuum and the ability to process difficult-melt and difficult-to-process materials that conventional processes cannot process.

Almost any geometry can be manufactured with high precision, and a wide range of metals are used, including the lightest titanium alloys and the strongest nickel high-temperature alloys,which are difficult to process by conventional manufacturing techniques. The mechanical properties are comparable to those of forged metals, and can be machined, coated, and treated just like conventionally manufactured metal parts. The disadvantages are the operational costs in fact, specialized equipment and vacuum systems are required, and the printed parts are limited in size and parts must be attached to the build plate by a support structure (to prevent warpage), which generates scrap and requires manual post-processing for removal; strong X-rays are generated during the forming process and effective protection is required to prevent them from leaking and causing harm to experimenters and the environment.

Currently, electron beam melting can only be used for a limited number of metals. Titanium alloys remain the primary raw material for this process, although cobalt-chromium alloys can also be used. This technology is primarily used to manufacture parts for the aerospace industry.

The advantage of the EB-PBF is that small parts can be stacked without adding the support structure commonly found in the L-PBF. Moreover, the electron beam penetrates deeper into the powder material than a laser, resulting in a more uniform powder melting. The electron beam can also melt highly reflective materials without causing surface overheating of the powder particles to evaporate. The EB-PBF has high productivity and can accommodate a wide range of layer thicknesses. The efficiency and surface finish balance can be flexibly adjusted to the specific application requirements. The melting process is carried out in the cleanest and safest high vacuum environment. In addition, the vacuum insulates the heat and contributes to energy efficiency. It is easier and less expensive to increase power with electron beams than with lasers. EB-PBF has greater scalability than L-PBF for future ultrafast AM and may compete with traditional manufacturing technologies in high-volume applications. EB-PBF is a hot powder bed process that maintains high temperatures throughout the forming process, resulting in parts with no residual stresses. This eliminates or reduces the need for heat treatment, provides significant savings in heat treatment time and cost, and facilitates greater design freedom.

Thanks to the superior temperature field control of EB-PBF, brittle and fracture prone alloys can be successfully additively manufactured, thus extending the application of additive manufacturing to materials that cannot be manufactured by any other process, including L-PBF. Although both L-PBF and EB-PBF have the basic function and form of selective melting of metal powder layers, there are systematic differences between the two technologies.The most significant difference is that L-PBF requires a mechanical oscillator to control the vectorial scanning of the laser beam. In EB-PBF, the deflection of the electron beam has no mass and no inertia, thus allowing the beam to scan the entire forming area almost instantaneously and to generate dozens of melt pools at the same time.

3D printed generative and bespoke orthoses made by PBF

2.5 DED

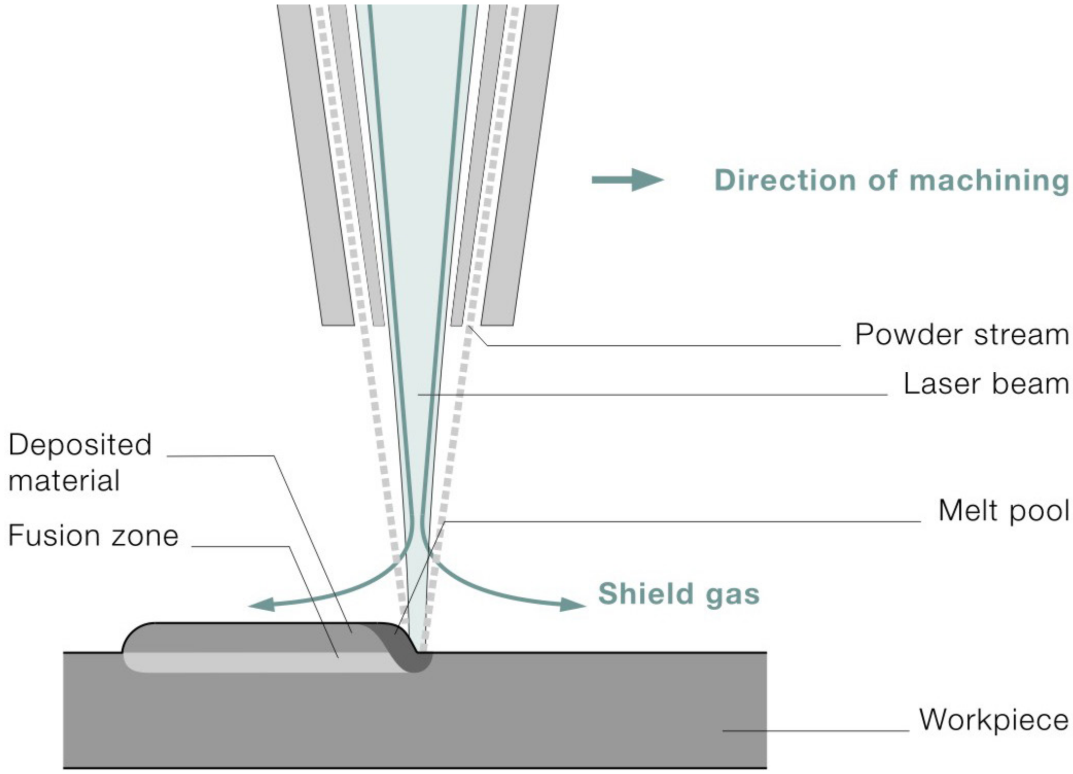
Directed Energy Deposition (DED) is an AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited.[27] DED has a higher deposition rate then the PBF techniques and is not limited by the size of the forming bin, and allows for the manufacture of large metal parts.[28]

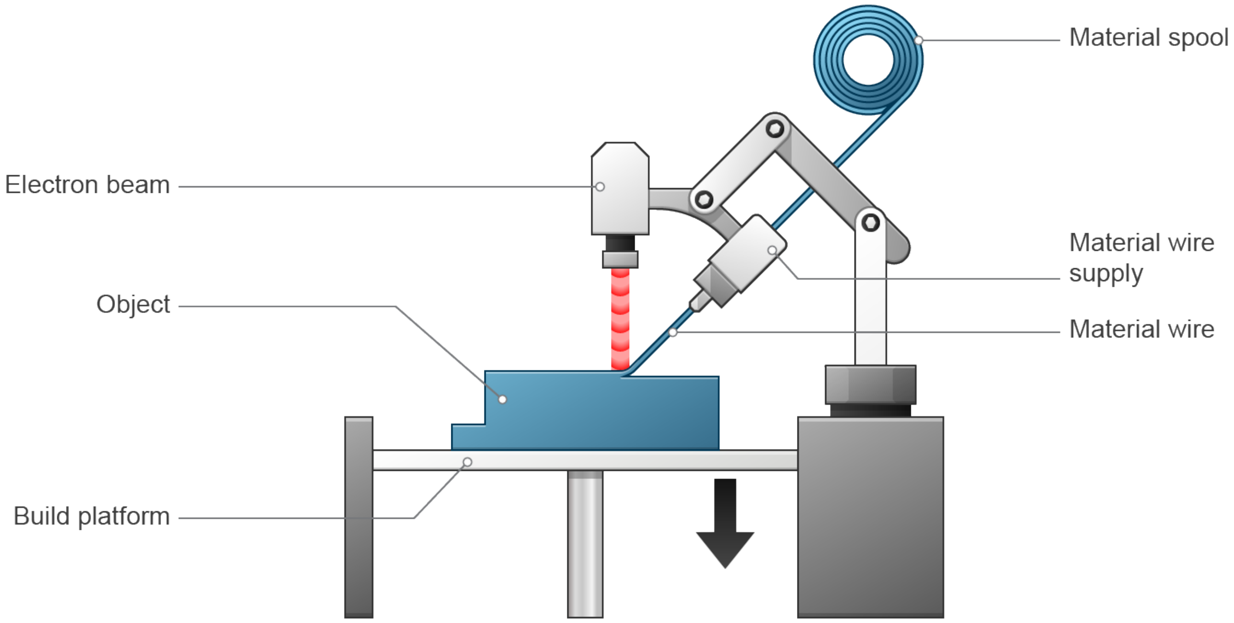
In the case of DED with wire as the material,there are three different energy sources for printing, mainly E-Beam as the energy source, Electron Beam Freeform Fabrication (EBF3), Arc or Plasma as the energy source,Wire-Arc AM (WAAM), laser as the energy source, and Wire-Laser AM (WLAM). Laser AM (WLAM), and one that also uses a laser as the energy source, but with metal powder as the material is Laser Powder DED (LP-DED).Laser Metal Deposition (LMD) technology uses a laser as the heat source and a metal powder or wire as the raw material for processing. The material is ejected from the nozzle by a protective gas, which is heated and melted at the laser focal point to form a molten pool, which is surrounded by the protective gas and moved forward by the laser, where it cools and solidifies to the substrate. [29] Parts can be formed without subsequent processing or with minimal handling to meet the requirements of use. It is a technological development based on new manufacturing technologies, simulation analysis and mechanical automation.

Compared to PBF technologies, DED technology is close to near-net forming and has a material utilization rate of over 90%. [30] The flexible movement of the laser head during LMD forming opens the door to increased design freedom and the production of large metal structures. DED deposition of single-layer thickness up to 1 mm, deposition rates up to 0.5 kg/h, and a very large range of motion, but with low forming accuracy and poor surface quality. [31]

In addition, another major application for DED is the fusion coating of enhanced coatings on the surface of various metal parts. in the ultra high speed laser cladding process developed by Fraunhofer in 2017, the powder is fed into a focused laser beam instead of a molten poolon the substrate surface, where the powder ismelted in the laser beam and then fell to the substrate in a molten state to cool and solidify.This small change makes a huge difference, as the scanning speed of the laser has less influence on the melting of the powder, and the flight time of the powder in the laser becomes an important factor, as long as the powder is fully melted, the scanning speedof the laser can be increased to more than100 times the traditional melting, which significantly improves the efficiency of the melting,reduces the production cost, and has become a promising alternative to electroplating. It is now a promising alternative to electroplating.

The Wire and Arc Additive Manufacturing (WAAM) technology uses a welding arc as the heat source to melt the wire material and stack each layer on the substrate according to the set forming path, and the layers are stacked until the metal part is

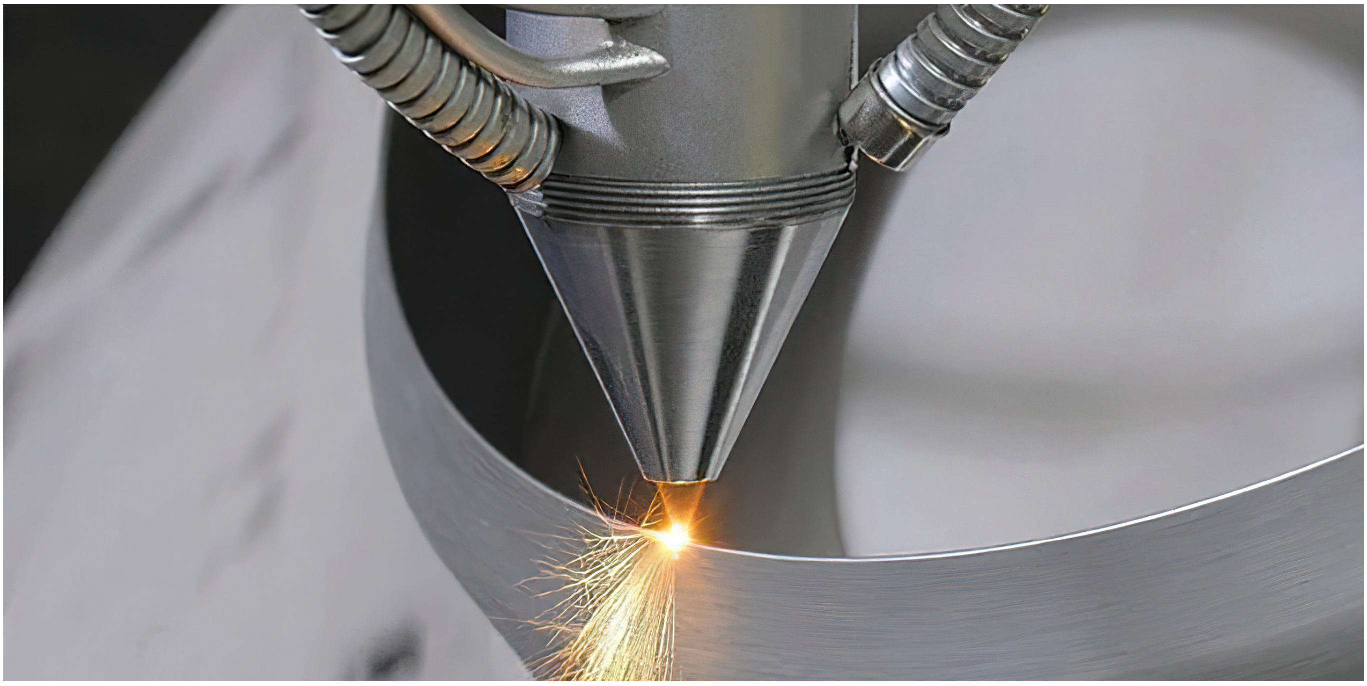




Direct energy deposition overview

formed. Compared with other additive manufacturing technologies using powder materials, WAAM has a higher material utilization, high construction efficiency,low equipment cost, and basically no limitation on the size of the part.

Electron beam fused wire deposition manufacturing (EBF3) is the application of electron beam welding technology to AM, in which a high-energy electron beam is used in a vacuum environment to the electron beam is used to bombard the metal surface to form a molten pool. The melt pool is formed when the wire melts, and droplets enter the melt pool under the electron beam heating conditions. Electron beam as a heat source has a higher energy density and can be used as a heat source. The electron beam as a heat source has a higher energy density, and the metal material does not reflect the electron beam,so the process is the most efficient. The melt pool formed by this process is relatively deep, which helps to the melt pool formed by this process is relatively deep, which helps to eliminate the phenomenon of unused layers, resulting in good internal quality of the formed part and less residual stress.The internal quality of the formed parts is good, and the residual stresses are lower .At the same time, the vacuum processing environment is suitable for reactive metals such as aluminium and titanium. The vacuum processing environment is suitable for processing reactive metals such as aluminium and titanium. However, the vacuum requirement also severely limits the size of the part and leads to costly production equipment. [32]



The DED process allows users to repair existing metal parts

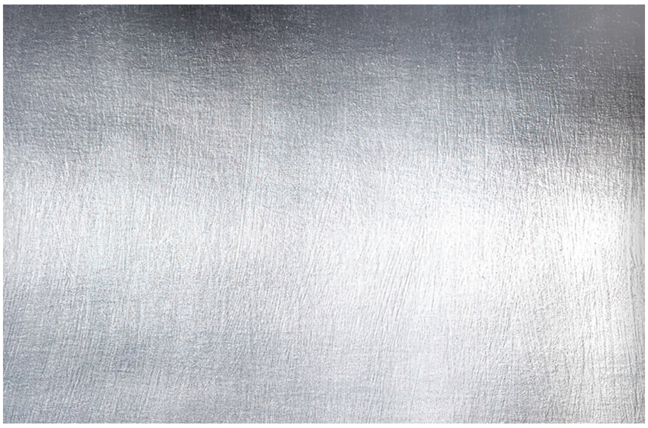
LASERDYNE-811 of PRIMA ADDITIVE company

2.5.1
DED material

For metals, virtually any weldable metal can be 3D printed using DEDs. This includes titanium and titanium alloys, inconel,tantalum, tungsten, niobium, stainless steel, aluminium,and more. The wire used is typically 1-3 m in diameter, and the powder particle size is similar to that used in powder metallurgy processes, between 50 and 150 microns.

However, processing powder shave many disadvantages. Powders are much more expensive than wire because DED is typically used to make medium to large parts that use large amounts of material. Also, not all of the powder ejected through the nozzle is captured in the melt pool. For free-form manufacturing, the actual powder utilization efficiency is 20-80% and is highly dependent on part fineness and process parameters. This is an issue from a material cost perspective and an engineering perspective.

From the user's point of view, there is also the need to dispose of unused powder, and the powder material may pose a health risk. In comparison, the wire utilization rate is 100%, while the wire material does not pose any risk. While the advantages of the wire printing approach outweigh those of powder printing, the powder is still more appropriate for some applications. When adding materials to highly irregular surfaces, powders will be a better choice if precise nozzle-to-part distances may not be available when coating or repairing certain parts. While many alloys can be used as wire,some more specific materials may only be available in powder form.



Steel alloys

Titanium alloys

Copper alloys

As a 3D printing technology, WAAM is capable of producing unique shapes and fillings that cannot be achieved by forging. Because it does not require molds, dies or tooling, each print can be customized. This greatly reduces the cost of creating unique replacement parts or architectural features, and like other 3D printing technologies, WAAM engineers can take a multi-component system and redesign it to print in one piece, eliminating the need for assembly or welds. The most common metals used in WAAM today includes: titanium (TI-6Ai-4V, grade 5,grade 23), steel (maraging grade 250, duplex 2205, 2507, martensitic 410, austenitic 420).

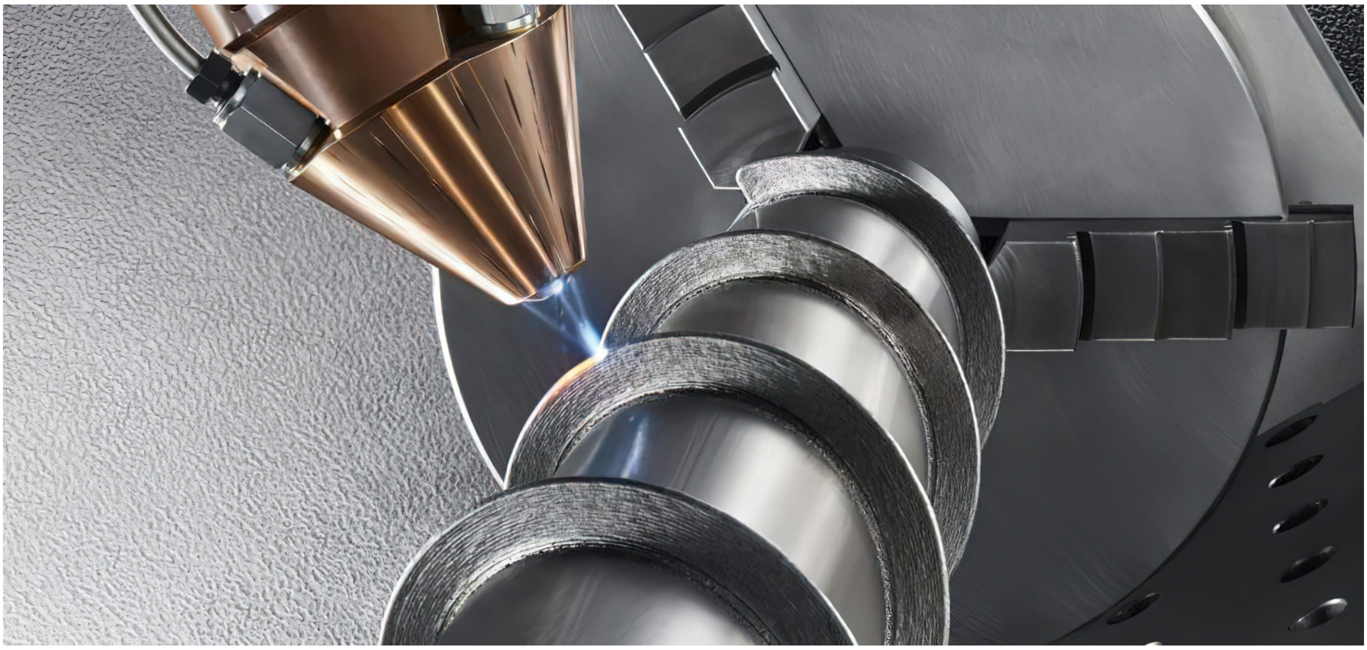
2.5.2
Advantages and disadvantages of DED

The main advantage of WAAM is the fast and economical printing of large metal items, but the appeal of the technology does not stop there. WAAM can be used with any weldable metal has a high deposition volume and rate (it can build parts quickly),which greatly reduces raw material use and waste and WAAM can make very large parts using existing arc welding technology,and WAAM supports design freedom and complex geometries. Most importantly WAAM technology is based on arc welding,so material and process behaviour is known so there is no shortage of industries that can use large metal parts and replace them faster.From defense and marine to construction and aerospace, all use WAAM to rapidly fabricate large metal parts, remanufacture heavy industrial parts, create unique metal features,repair molds, and repair or repurpose metal parts on-site, WAAM is making inroads into traditional manufacturing, but not entirely without challenges. Efforts are being made to increase speed and simplify the software,while research and development moves WAAM from a single-piece or low-volume production method to mass production manufacturing.

However, for more significant volume parts, WAAM is not an economical option compared to traditional methods because once a forging or casting mold is created, hundreds or thousands of parts can be produced faster through casting. WAAM cannot compete with powder bed fusion technology in terms of accuracy or with electron beam DED processes in terms of speed. Currently,WAAM is focused on the growing adoption of metal forging and casting as applications for high-risk operations in today's supply chain-constrained environment. As bringing production closer to the point of demand becomes increasingly important, both economically and environmentally, WAAM offers solutions that can prove themselves in each new application.

Overall, DED can achieve competitively advantages over traditional markets by shortening part development cycles and production lead times, reducing time-to-market,and reducing the need to store spare parts. In the future, the technology can be used to produce high-performance,high-value-added components that offer greater design and material freedom using this technology. For example, optimizing components for structural or thermal loads,or producing parts using custom alloys or combinations of several alloys, DED improves sustainability by increasing the material efficiency of the manufacturing process, i.e. deposited parts (called nearest shapes, preforms or deposited models) require significantly less material removal to obtain finished parts compared to machining parts from material blanks.

In the future, DED and other metal AMs offer a decentralized production model, meaning that instead of parts being produced in a single plant and shipped to the end-use location, they can be produced on-site when needed, reducing the time required in transit and reducing carbon emissions.



DED

Optomec DED based LENS technology, 3D printing onto a premade metal surface

2.6

How to choose technology correctly

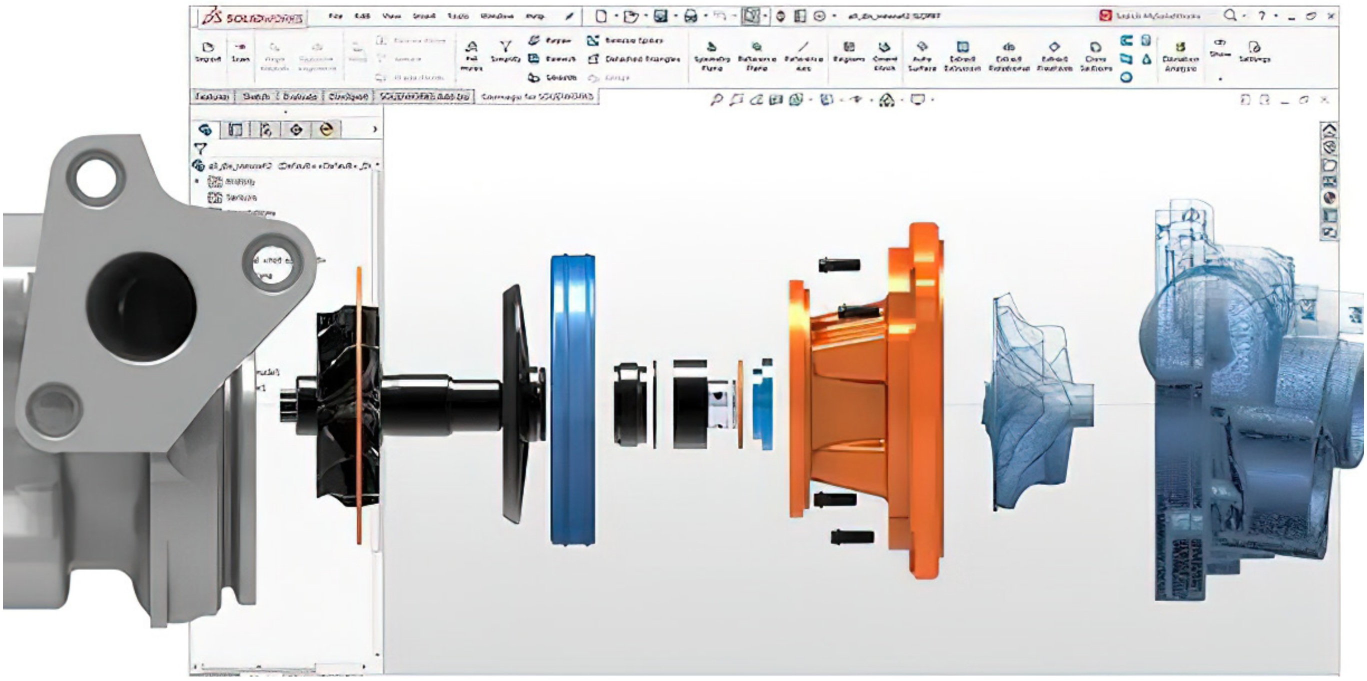
Currently, there are many different methods on the market to 3D print metal parts. These methods are roughly divided based on the form of raw material used and the energy source, such as whether the material is wire, metal powder, or metal wire, and each method can create parts with different properties. The choice of which metal technology to use requires consideration of part detail, shape,size, strength, metal type, cost, print speed and quantity. When analyzed in these terms,each technology has pros and cons, and unfortunately, no one method can3D print super-strong parts quickly, cheaply,and perfectly, so the choice of exactly which technology to use is based on the needs of the application. The 3D printing market offers a wide range of 3D printers, materials, service agreements, and software at a wide range of prices. If you are not familiar with 3D printing,the number of options can be overwhelming .Even for those with some 3D printing experience, choosing the right 3D printer can be daunting. Many factors must be considered, including noise levels, safety compliance, technical specifications and production parameters.

The first step is to determine the printing needs and whether the print is for mass production or has extremely high aesthetic requirements, all of which can quickly filter out different printing methods. Further, for the size of the print object, the maximum print range of the printer needs to be determined, or if multi axis printing is required; such a selection is heavily biased towards DED printing methods. For example, huge crane hooks are printed with arc additive manufacturing (WAAM) and then post-processed. A huge and heavy part like this is ideally suited for WAAM because the technology is faster than any traditional metal fabrication method (such as forging or casting) and just as strong. In addition, such parts can be produced in a factory close to the point of demand, or even on-site, for example, on an oil rig.

Crane hooks printed with WAAM 3D printing technology

The choice of material is also one of the points to be considered when the production the object must be made of refractory metals, the range of printing options is narrowed to L-PBF, which prints objects in order to get better mechanical and stability, an application in the professional range, and on the other hand raises the material cost.

Not all characteristics of metal 3D printing technologies are measured in the same way,especially regarding building speed. Some technologies record the build speed by the weight of the deposited material, while others measure it in terms of the volume of material formed. These speeds are also influenced by the shape of the part being printed. In addition, it is unlikely that every 3D printer in technology will achieve the same speed.Layer height, which is usually a parameter of the ability to print fine details is affected by the material used and the shape of the part. Moreover, the speed at which it is printed. Before investing in any one technology, ask for sample parts (identical parts) from multiple 3D printer manufacturers. The sample part should come with a report on how long it will take to print the part, how many parts of that size and shape, the printer can print at once, the price per part and the material consumption so that you can choose exactly what you need to print.



SOLIDWORKS

2.7
Other technologies

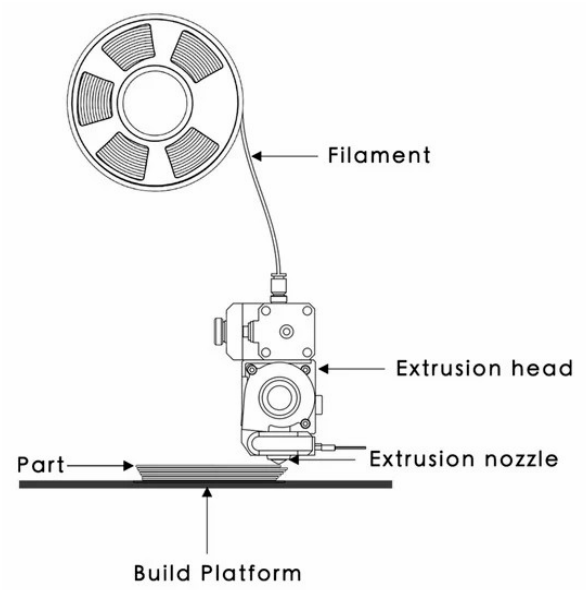
Binder Jetting is additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials. [33] Similar to the SLS process, powdered materials are used to form the part, except that the powdered materials are not sintered together, but rather the cross section of the part is "printed" on top of the powdered materials with an adhesive (e.g. silicone) through a nozzle. The adhesive spray process uses two materials; One is powder material and the other is adhesive. The binder acts as an adhesive between the powder layers. Adhesives are usually in liquid form, while building materials are in powder form. The print head moves horizontally along the X and Y axes of the machine, alternately depositing construction materials and adhesive layers. After each layer, the printed object is lowered on its construction platform. Due to the bonding method, the characteristics of materials are not always suitable for structural parts. Although the printing speed is relatively fast, additional post-processing will add a lot of time to the whole process. Like other powder based manufacturing methods, the printed object is self-supporting in the powder bed and will be removed from the unbound powder once completed. This technology is often referred to as 3DP technology and is copyrighted under that name.

VAT Photopolymerisation is a technology encompasses several different process that rely on the same basic strategy: a liquid photopolymer contained in a vat (or tank) is selectively cured by a heat source. Layer by layer, a 3D physical object is built until completion. [34] Special resins called photopolymers are used as print media in all forms of vat photopolymerization printers. When exposed to specific wavelengths of light, liquid photopolymer molecules rapidly bind together and solidify into a solid form, a process called photopolymerization. Most 3D printers that use vat photopolymerization keep the liquid photopolymer in a container or vat, with the build platform partially submerged on the surface of the liquid. The printer uses the information in the CAD file to guide the light source to selectively cure the liquid photopolymer into a solid layer. The build platform is then re-submerged in the remaining resin and the process is repeated for subsequent layers until the design is complete. The most dominant techniques are SLA, DLP, CLIP and DPP, which were discovered in the early 1980s by researchers in Eben and France. It is now used successfully in medical modeling for precise modeling of various parts of the patient, and has the advantage of high resolution and fast printing, making it ideal for jewelry, dental and medical applications.

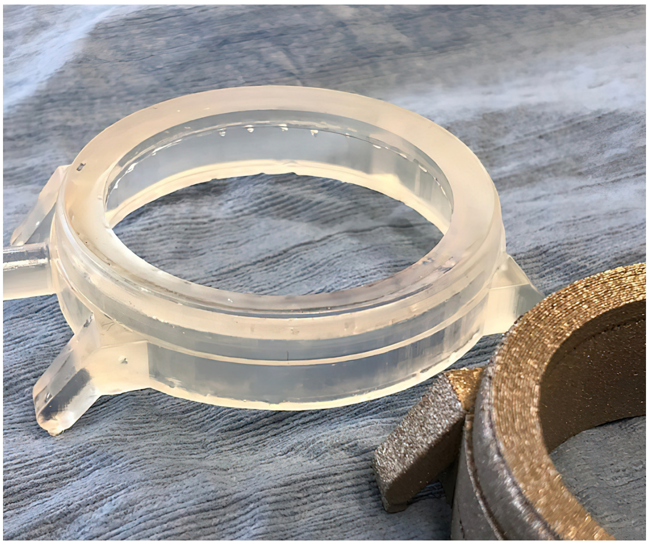
Binder Jetting

Material Extrusion is additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.[35] Material extrusion (me) is the second most popular form of additive manufacturing (AM) process. The process allows the use of a variety of materials with different properties and characteristics, from commodities and engineering to high-performance thermoplastic, composite and functional materials. It is used in fast and low-cost printing design, and has a great degree of freedom. It can print parts of different shapes and sizes, but the accuracy is not high, which is not suitable for the production of complex or miniaturized parts. The appearance is not smooth, and the fusion of each layer of materials is not completely dense, and the structural strength is not high.

Material Jetting is additive manufacturing process in which droplets of feedstock material are selectively deposited.[36] The material must be deposited in droplets, it is available in a limited number of materials such as photographic resins, waxes or metals, and it is possible to use different colors in the technology center, so it is possible to print full color and transparent parts. It was created by the Israeli company Objet Ltd. His printing benefits from the high precision of droplet deposition, so there is less material waste, material is deposited from the nozzle, which moves horizontally on the build platform and finally hardens the material using UV light curing.



Material Extrusion



Vat photopolymerization's high resolution makes layering effects almost invisible

Future of metal AM

03

Chapter

3.

Future of metal AM

With the increase in demand for metal3D printing, the types and forms of metal 3D printing materials have been rapidly expanding, and the price is expected to drop,and the precision, strength, stability and safety will be more secure. Metal 3D printing has strict requirements for the shape of the material, generally powder, filament,which is relatively expensive and cannot meet the needs of individuals and industrial production and affordable materials can provide a large enough choice for the development of technology and provide a large enough imagination for the expansion of applications.[37]

Metal 3D printing is revolutionizing traditional manufacturing with its layer-by-layer stacking technology. As metal 3D printing continues to evolve, forming methods will become less and less limiting in the areas of part design and manufacturing and more energy will be devoted to exploring the functional aspects of parts and materials. Whether laser-selective melting metal 3D printing will continue to be a leader in metal 3D printing in the future is unknown, but the key factor is how quickly the technology evolves. The following are some of the trends in metal 3D printing technology in the coming years:

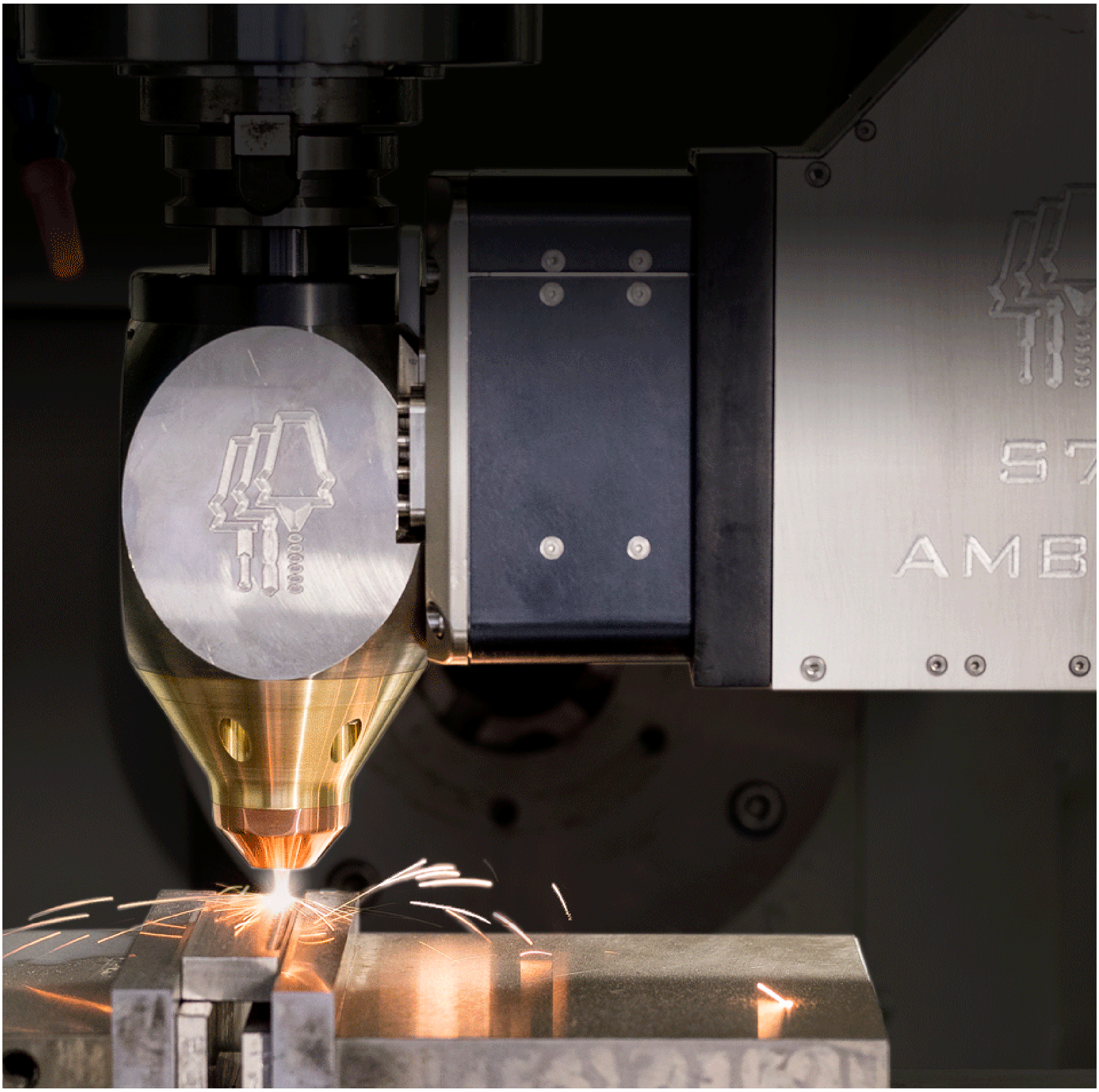
Metal 3D printing equipment is further subdivided. Such as forming small size, low laser power, high surface quality requirements of titanium alloy dental special metal 3D printing equipment; specifically for plastic mold with the shape of the cooling water channel forming metal 3D printing equipment; specifically for titanium alloy large parts forming multi-laser head metal 3D printing equipment; specifically for the aero-engine blade precision repair metal 3D printing equipment.

Metal 3D printing miniaturization, desktop. With Hewlett-Packard, General Motors and other Fortune 500 companies to enter the metal 3D printing industry, the price of lasers and related hardware decline, metal 3D printing equipment prices will drop significantly, desktop-level small metal 3D printing into thousands of households.

The development of Hybrid manufacturing (HM) technology, which combines different 3 printing technologies use the combination of both technologies to overcome their respective limitations, such as low productivity, metallurgical defects, rough surface quality, and lack of dimensional accuracy, while benefiting from their inherent advantages. This approach also increases the flexibility of the technology and reduces the material waste associated with traditional manufacturing processes. For example, DED and SLM are two popular metal printing methods, where DED can be used for a wide range of metal materials, and SLM can have high dimensional precision printing. However, SLM is time-consuming, and the cavity of the machine limits the size of the parts that can be produced. The biggest drivers for HM technology is flexible and cost savings to speed production-to-market time.[38][39]

Metal 3D printing technology and the

integration of a variety of technologies. Integrating metal 3D printing technology with precision cutting, heat treatment, surface treatment, and other technologies allows the expansion of forming methods.[40]



Hybrid Manufacturing from AMBIT™

3.1
AM Metal trend

Although metal-grade AM can create microstructures that are not possible with traditional machining processes, and customer demand for additive equipment and services are growing rapidly, additive technology is still not a mainstream application.

One of the reasons for this is that current metal grade additive equipment has the limited product size to meet the needs of most industrial manufacturing. Smaller size additive devices are more often used for research and education, so in order to meet customers' needs at different stages from"concept exploration" to "prototype" to "scale production," device manufacturers need to develop a larger size of additive devices to meet their needs. Therefore, in order to meet the needs of customers at different stages from "concept exploration" to "prototype" to"scale production", equipment manufacturers should continue to explore the development of larger molding size equipment. The metal AM industry is in the process of changing from "research-based"to "manufacturing-focused". Large-size, multi-laser, digital, high stability, intelligent,customized, user-friendly additive devices represent the future competitiveness of AM, which can reduce the difficulty of using equipment, reduce loss by timely detection of problems in production, improving printing speed and print quality, and meet the manufacturing needs of larger-size parts.

Secondly, metal-level additive manufacturing equipment is mainly made of a combination of software, scanners, substrates and other components. The core patents of AM mainly comes from midstream equipment manufacturers, while midstream equipment manufacturers continue to expand upstream and downstream to master raw materials suitable for AM and advanced additive service process technology methods through industrial integration or mergers and acquisitions, so a sto better prepare for equipment updates and iterations.

As the development of the metal additive industry matures, and the number of participants increases, the application areas of different metal additive technology lines begin to overlap. The intensification of competition has led to the elimination and consolidation of technology lines within the industry, and additive technologies with high cost performance and uniqueness are further developed and eliminated.

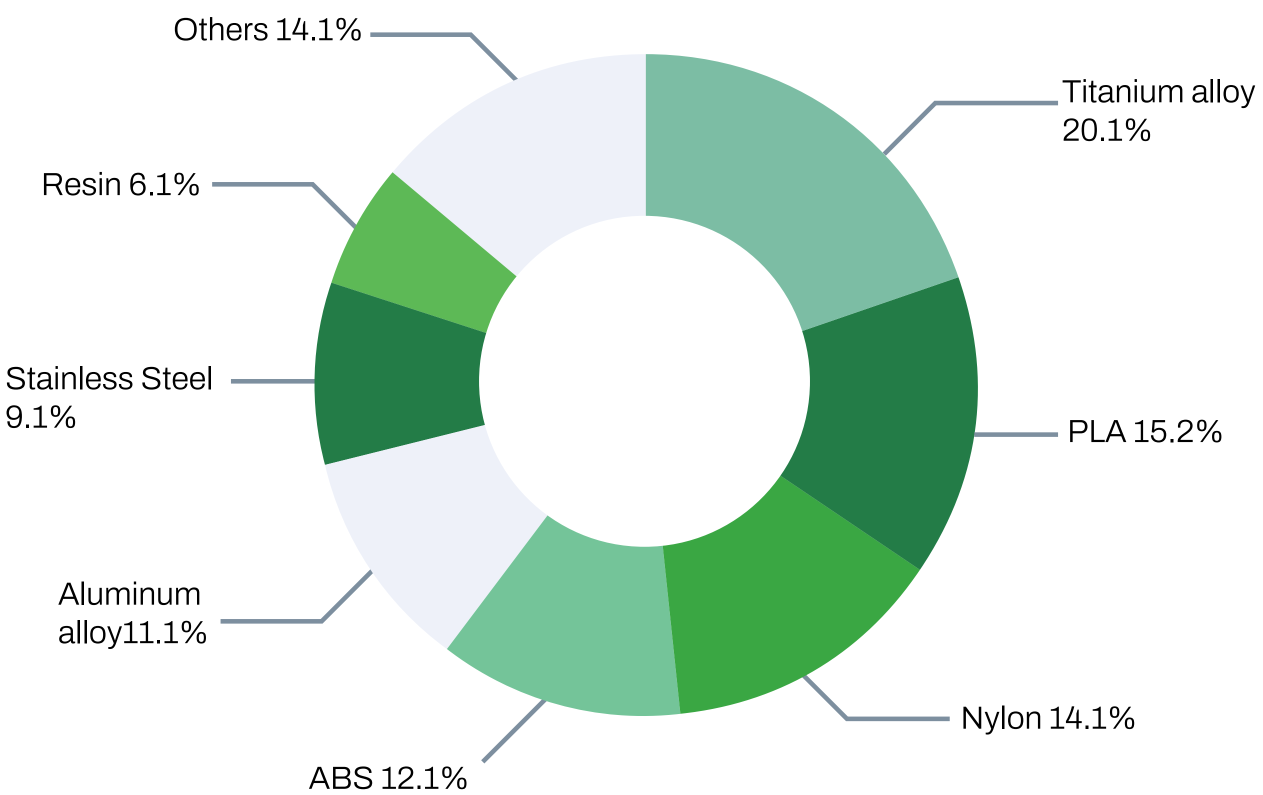
Software development is an important guarantee for metal AM, because software development is a significant investment and requires constant maintenance every year, which is a capital and technology-intensive industry. Metal AM software mainly includes :system software, slicing software, three-dimensional drawing software, generating G code software (used to guide the servo operation). And software costs account for nearly 20% of the cost structure of metal AM equipment. In China, the software is one of the shortcomings of the whole AM ecological industry chain, and software development still focuses on academic research. At present, the system software mainly relies on foreign mature operating systems installed, such as the Siemens system. So in the case of China, AM equipment factories are the main force of software development. Matching self developed equipment with the software of their own intellectual property rights can reduce the production cost of additive equipment on the one hand, the income from equipment sales provide a financial guarantee for software development on the other.

Furthermore, the government's promotion, with the help of sponsorship provided by the government will more than likely stimulate the development of this industry, for economic stimulation, transition and construction can also promote and help 3D printing companies has provided a vision in line with the national interest,these programs can help integrate business and academic research resources that would otherwise not be available to a single company or university. The recent federal support to AM and advanced manufacturing is being directed to rebuild and revitalize manufacturing bases, stimulate the economy,restore, and stimulate manufacturing job growth. [41]

Also, with the help of the government,universities around the world can receive financial support to address issues including materials, software, modelling, sensors, hardware integration, and process development. Setting up a Google Scholar the alert is a great way to keep abreast of scientific and technical advances. Open-source technical papers and PhD dissertations are sources to digging deeper into the challenges faced, the questions being asked, those answered, and proposed solutions.

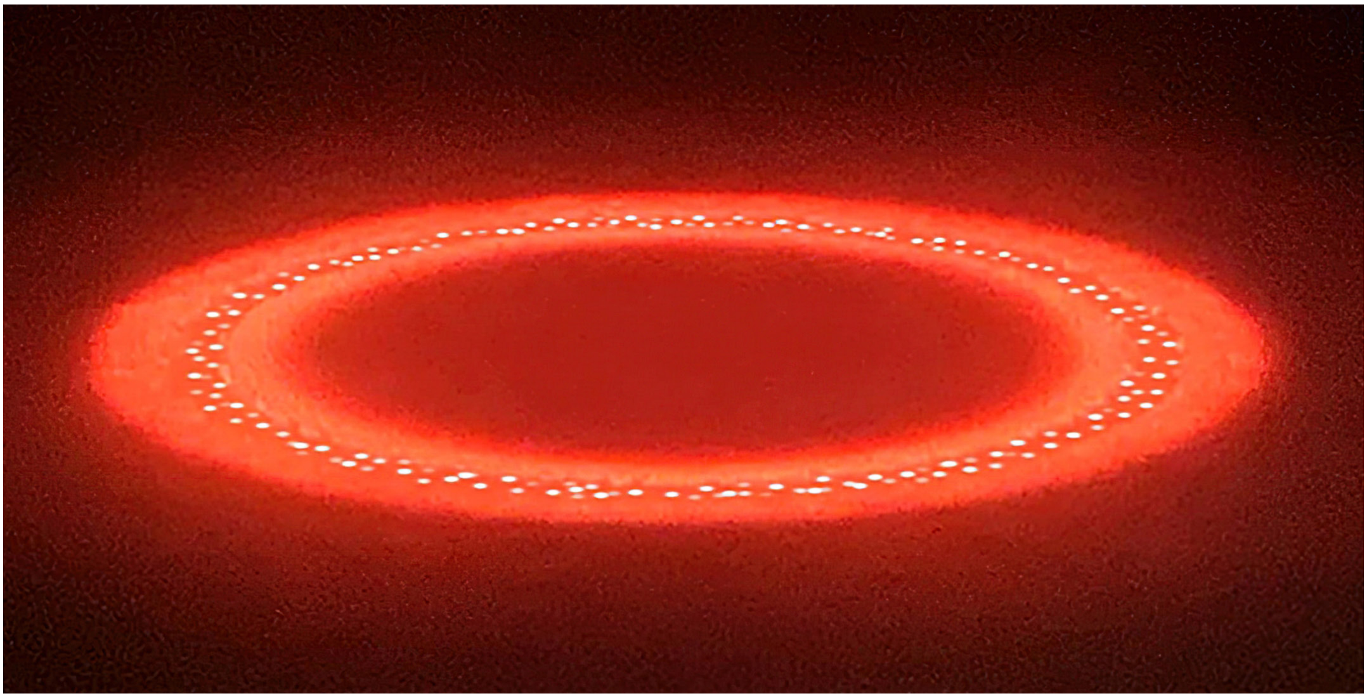
The figure shows a schematic diagram

Sample orthopedic implants 3D printed in titanium by Zenith Tecnica using GE's electron beam melting technology of the statistics of the value share of 3D printing materials in 2018. In terms of current statistics, the share of the manufacturing industry using 3D technology is still a minority,one of the most important reasons is the limitation of printing materials, 3D printing materials can be divided explicitly into metal consumables and plastic consumables from the type. Currently, metal materials are expanding rapidly in the 3D printin G the technology industry, but due to the limitations of the material properties, so it is mainly used in the production of molds, but metal 3D printing can be both mold-free customs 3D printing materials in 2018 advantages, its printing effect and print quality compared with the traditional process, also has a significant improvement, so metal 3D printing technology has greater potential. [42]



3D printing materials in 2018

WAAM steel parts from MX3D



Freemelt's Pixelmelt software provides users with greater freedom in process optimization

3.2 Technology development

At present, metal 3D printing is really in the bottleneck of development because of some unavoidable reasons.
The current stage of high printing costs (equipment, raw materials, high cost of use). Metal 3D printing technology mainly in the difficult processing of high-performance, expensive, other methods cannot be processed parts do have certain cost advantages, but in the daily metal supplies, the cost is very much higher than traditional processing, even up to 1000 times. In addition, metal powder is basically around 150 $ / kg, and the price of metal 3D printing equipment itself is relatively high, the minimum price is about 285,841 USD. Therefore, reduce the cost of metal 3D printing for the expansion of its application areas is of great importance, but also the development of metal 3D printing technology must go through.

Material research and development. One of the cores of 3D printing technology lies in the material and the traditional metal powder used in powder metallurgy can not yet fully adapt to the requirements of 3D printing, and can be used to print a small variety of metal materials, the price is high. Now there are a few companies specializing in metal powder for 3D printing,such as the United States Sulzer Metco, Sweden's Sandvik but can only provide a few conventional metal powder. [43] Airbus has proposed the concept of printing an 80 m x 80 m functionally and structurally integrated aircraft by 2025. However, the aircraft inside the skin (composite materials),circuitry (plastic, metal materials), piping (metal materials), how to use 3D printing technology for multi-material coupling is worth exploring.The reason why the printing powder is expensive is because the material development cycle is long, and the research and development is more complex than the equipment and companies are reluctant to carry out material development for the sake of maximizing profit. There are a few companies have in the development of diamond micro powder, CBN micro powder production. But university research and keen on 3D printing equipment and software packages, so the printing materials, to a large extentrestrict the development and application of metal 3D printing technology.

The optimal forming parameters for various metal materials vary. There are differences in the properties of different materials, and a lot of experimental tests are needed to explore the optimal process parameters for each metal. This also makes the urgent need to solve the problem in order to make 3D printing have better development.

Solidification organization, internal defects quality. Printed parts exist spheroidization,internal porosity, deformation and cracking Future of metal AM 70 problems make its mechanical properties can not meet the industrial requirements,especially heavy load, high impact and another harsh working environment of high end structural parts requirements are not met. At present, the solidification law of the internal organization of printed parts and the mechanism of internal defect formation,internal stress evolution, grain morphology,grain size, grain orientation control methods during the printing process are still not clear enough, and needs to be studied in depth.

Complex post-treatment process. In order to improve the surface quality, eliminate the step effect and internal stress, metal 3D printing usually requires manual polishing, electrolytic polishing, heat treatment, wire cutting and other post-treatment processes. For the complex surface of the workpiece, it is very easy to clean up dead ends.

Intelligent material development. MITproposed the concept of 4D printing, and successfully used hydrophilic intelligentmaterials for printing out structures that can deform over time. 4D printing technology will have a profound impact on the traditional mechanical structure designand manufacturing, and has unparalleled advantages over other manufacturing technologies in the fields of aerospace,biomedical devices, intelligent robotics,structural health monitoring, energy recovery. Therefore, it is crucial to expand the application of 3D printing technology to the highest point and strengthen the development of intelligent materials.

Nano 3D printing technology, microscale 3D printing is also an important development direction. [44]

At present, the metal additive manufacturing technology used in the manufacture of weapons and equipment parts at home and abroad are mainly 3D printing, which means that the structural parts of the required shape are manufactured by stacking layer by layer, focusing on the shape and mechanical properties of the structural parts, and their shape, performance. In recent years, 4D printing technology has been developing rapidly and has become an important development direction for AM technology. Compared with 3D printing, and 4D printing introduces a time dimension in three-dimensional space, and enables controlled changes in the structure,performance and function of components inspace and time dimensions through active design and manufacturing of materials and structures.[45]

3.3
AM Metal in different countries

Metal 3D printing is growing rapidly in many parts of the world, such as the United States where the "Made in America"program is funding a wide range of technology development activities focused on overcoming engineering challenges to advance 3D printing and AM technologies. Overcoming engineering challenges to advance 3D printing and AM technologies. Some examples include the development of AM materials, scaling of AM system size and speed, integration of AM hardware with hybrid machines, integration of in-process real-time quality assurance systems, and the creation of new computational model sand databases for AM processes. And AM process databases. Benefits include technology spin-offs, the creation of large and small partnerships, and the creation of larger markets.

And in recent years, with the expiration of patents on core technologies, the commercialization of metal 3D printing has accelerated significantly. From the application point of view, the commercialization of non metal materials are earlier, but with the gradual maturity of metal printing technology, SLM technology (expired in December 2016) as the representative of the patent expiration, its commercial application in recent years began to accelerate. According to the judgment of Wohlers, Gartner and other research institutions, the growth rate of global AM in the past three years will be maintained at a 20%-30% growth level,of which metal 3D printing driven by the demand for industrial-grade 3D printing will be maintained at a 40% growth level. In China, the AM industry is becoming increasingly mature, and more companies and institutions are joining the ecosystem of AM. Except for a small number of core components that still need to be imported, the whole industrythe chain can be self-reliant. With China's increased investment in the AM industry and policy guidance, China's independent research and development capability in AM has continued to improve,and has reached the international advanced level in fused deposition forming, light-curingforming, laser-selective sintering/melting and other technical routes. Especially in the field of metal AM, the development is rapid, and the market shows a high growth trend.

At present, China's near-net forming technology route from additive equipment to service, process is in the global leading the level is currently one of the few countries in the world to master the manufacturing of 2 meters and above specifications finished products. China's SLM technology is slightly behind German companies in terms of equipment, but its research and development in the molding process is not inferior to foreign companies. In addition, Chinese metal raw materials for additive manufacturing have been replaced by localization,and industry standards are gradually being established. The universities are also developing new printing technology, Xi'anJiaotong University proposed cold supersonic jet printing and forming technology; University of Science and Technology Beijing Institute of New Materials Technology to carry out research on 3D cold printing technology of metal-based composite materials, using the effect of the combination of metal and metal,metal and non-metal to produce a variety of composite materials and exceptional performance materials. In the comparison of the total number of patent applications, it is not difficult to find that the number of Chinese patents significantly exceeds that of the United States, which on the one hand, indicates that the Chinese 3D printing industry is in a stage of rapid development, and on the other hand,there are also factors of the patent layout by foreign companies in China.

Comparing the structural differences between the U.S. and China, the Chinese the patent division is less numerous than the U.S., in terms of printing process reliability,but far more numerous in terms of reducing equipment and process costs and improving equipment reliability. The former is mainly since 3D printing technology originated in the U.S., which plays a leading role in the world in terms of fundamental patents and process innovation. The latter is mainly because Chinese equipment manufacturing enterprises have entered into a high-speed development channel in recent years and the layout of related patents is slightly behind that of the United States.

GE Additive has selected Imaginarium as its official sales partner in India to join its global network of sales partners. Imaginarium will resell GE Additive's portfolio of metal additive manufacturing machines and metal powders, which includes direct metal laser melting (DMLM) and electron beam melting (EBM) technologies. The products are targeted at manufacturers in a wide range of industries, including aerospace and defense, medical and dental, automotive, tool and die, and jewelry. GE Additive has selected Imaginarium as its official sales partner in India to join its global network of sales partners. Imaginarium will resell GE Additive's portfolio of metal additive manufacturing machines and metal powders, which includes direct metal laser melting (DMLM) and electron beam melting (EBM) technologies. The products are targeted at manufacturers in a wide range of industries, including aerospace and defense, medical and dental, automotive, tool and die, and jewelry. GE Additive's line of metal 3D printers is available in a variety of sizes, including large-format machines such as the X Line 2000R, and is particularly well suited for printing parts, components and systems for the aerospace industry. For more than a decade, GE Aerospace has been using metal 3D printing technology to mass produce functional parts for commercial and military aircraft engines. With India increasingly seen as a potential global manufacturing hub, access to advanced and up-to-date technologies for design, prototyping and production is critical for the industry. The Indian government's upcoming policy to promote additive manufacturing on an industrial scale will give a significant boost to the adoption of this technology.

3.4

Connectting with other industries

In recent years, countries around the world has attached great importance to the application and promotion of AM technology in weapons and equipment. The U.S. has formulated a series of strategic plans for the application of AM technology in the defencefield, and in 2016, the U.S. Department of Defence released the Additive Manufacturing Technology Roadmap, which analyzes the needs of defence AM technology and details the development goals in the technical areas of design, materials, process and value chain.[46]

In 2017, the U.S. Navy released the Navy AM Implementation Plan to identify long-term development goals for AM technologies.To promote the application of AM on ships, the Navy AM Plan was released in 2018, adding ship Am to increase maritime security capabilities. The U.S. Air Force has proposed an Additive Manufacturing Printing Strategic Plan to introduce critical technologies, development strategies, and goals for Air Force AM, with the hope of establishing a global manufacturing network in the future to enable on-demand printing processes, reduce costs, and effectively improve military flexibility.

The U.S. Army refined the domain requirements based on the DED AM Technology Roadmap, developed the Army Additive Manufacturing Technology Roadmap and introduced the application needs and goals of AM technology in the areas of Army maintenance and assurance, acquisition and deployment of new components/systems, and expeditions.2021 The U.S.A. Department of Defense released the AM Strategy, which introduces the meaning of additive manufacturing technology and its impact on defence strategy. It describes in detail the key development areas and path planning of AM, and proposes the future direction of development. [47]

Metal additive manufacturing technology provides new ideas and opportunities for the development of lightweight, strong protection, high damage, information and the intelligence of weapons and equipment, and has been applied to the overall rapid manufacture and repair complex parts of special steel, aluminium alloy, titanium alloy, high-temperature alloy, magnesium alloy and refractory metals, which has greatly improved the comprehensive performance of weapons and equipment and shortened the development, production and maintenance cycle. In addition, metal AM technology has successfully realized the design and preparation of high-performance metal materials such as high-entropyalloys, gradient materials and composite materials, which have broad application prospects in the fields of high temperature resistance, impact resistance and structural lightweighting of weapons and equipment. And the expansion of the metal AM service area promotes the renewal of the technology of the whole industry chain, and the aerospace military industry will benefit in priority.

At the current stage, due to the rapid

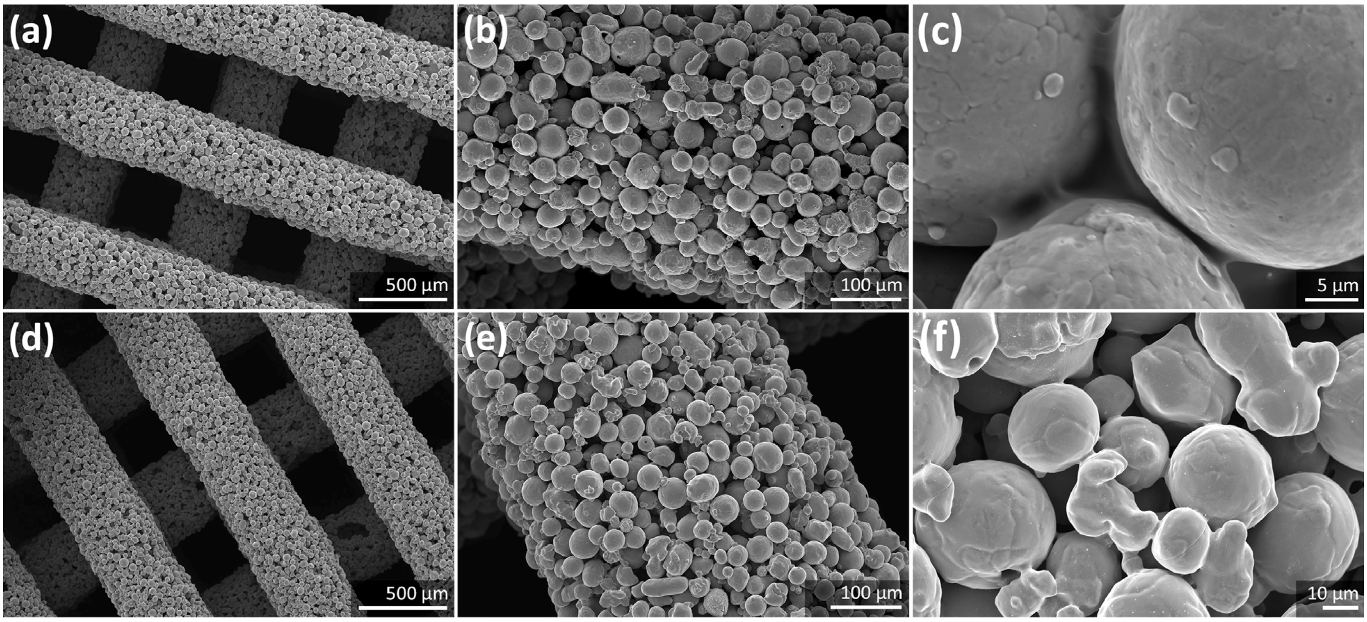
technological renewal, high R&D costs and small production volume, the currently acceptable industry sectors are mainly concentrated in aerospace and defence industry. Industry attributes determine the cost of construction is not the first sensitive element, but more focus on the overall reliability of the product, the optimization and upgrading of the structure, a significant reduction in weight, breakthroughs in large size specifications.

And with the gradual maturity of additive manufacturing, metal additive manufacturing enterprises have continuously carried out R&D, design, testing and trial production of military multi-model parts in recent years and Plutonium has even achieved batch production and supply, indicating that the application of additive technology has been recognized by the aerospace military experts. The AM technology of China Aerospace Science and Technology Group has been widely used in the development of positive and preliminary products in many fields, such as manned space flight, deep space exploration, remote sensing and communication, involving nearly 20 models and more than 300 pieces of parts. With the gradual finalization of military products of scientific research cooperation in recent years, it has been expected that military orders for additive manufacturing will achieve explosive growth and strong sustainability in the next 2-5 years, and aerospace, military industry is expected to become the first driving force for the rapid rise of metal-level additive manufacturing.In the medical field, the biodegradable metal 3D printing has become the future of research direction and development trend. Most of the medical metal materials currently used in clinical practice are traditional inert materials, including pure Ti and titanium alloys, stainless steel, and cobalt-based alloys. After implantation into the human body, they will exist as foreign objects in the patient is body for a long time or needs to be removed by secondary surgery at the end of their service.

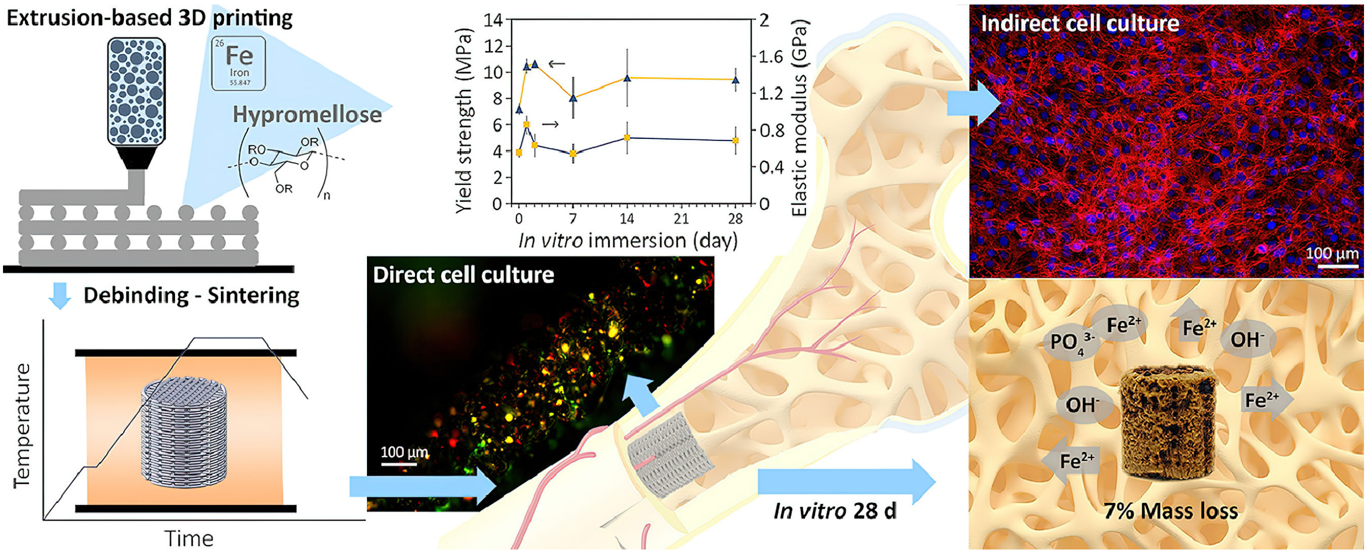
2019 defines biodegradable metals as a class of metals that can gradually corrode in the body, releasing corrosion products that cause an appropriate host response. These corrosion products can pass through or be metabolized or assimilated by cells and/or tissues and disappear completely without the residue after they have completed their task of assisting tissue healing. [48] Degradable metals, mainly include magnesium (Mg)-based degradable metals, zinc (Zn)-based degradable metals, and iron (Fe)-based degradable metals, and the mechanical properties of Mg-based degradable metals are most similar to those of human bones. Fe and its alloys have the most excellent mechanical properties in degradable metal systems and are comparable to traditional medical metal materials. [49]

For an ideal orthopedic biodegradablemetal implant, the implant needs to provide12-24 weeks of mechanical support depending on the clinical requirements,so there are requirements for aspects such as the corrosion rate of the bonus metal, but the vast majority of processes now target conventionally manufactured bulk metals. In addition to optimized alloy composition, structural design and AM processes, functionalized surface treatment is the technical key,and implantation in orthopedics for bone defect treatment is the most likely clinical application for breakthroughs. In summary,this is a challenging cross-scientific challenge that requires the intersection of materials,mechanics, information, biology, and medicine to accomplish.

Military 3D printing expected to reach 14.8% annual growth



SEM imaging of the porous iron scaffolds , this can be designed and manufactured to treat porous structural defects in critical bone



3D printing, sintering, and testing the porous iron bone implants

Ultimaker representatives with the newly launched Metal Expansion Kit for filament-based metal AM

Project

04

Chapter

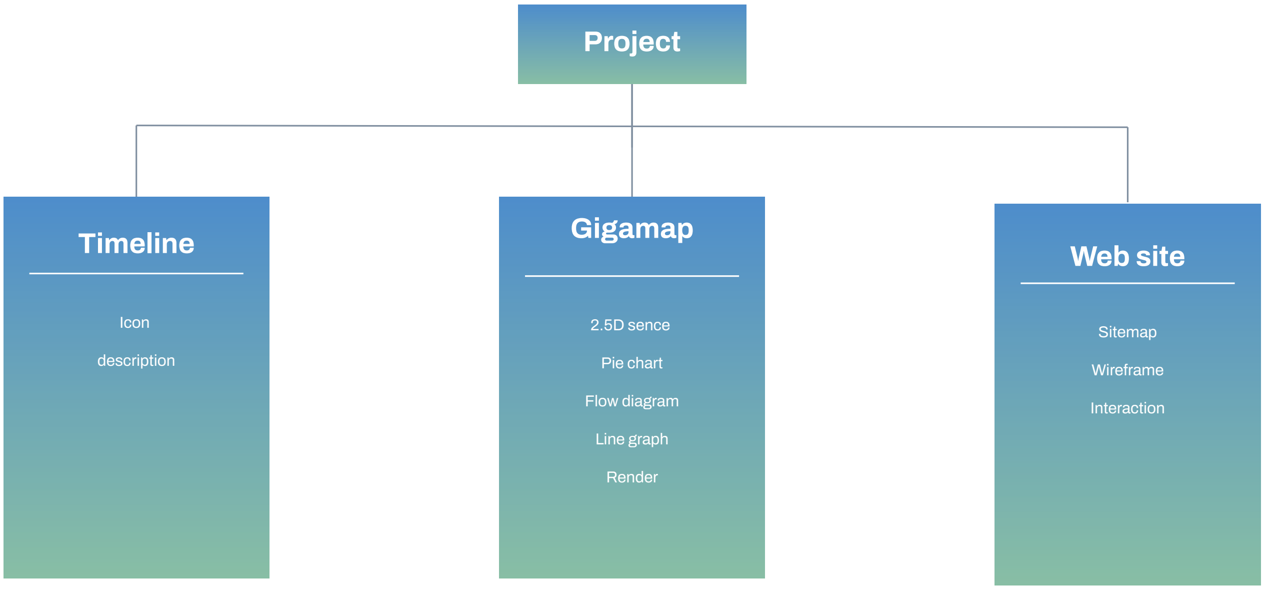
4.
Project

Based on our research, we found that there are many different types of metal AM technologies, each with its own advantages and disadvantages. We present our final results through a mix of graphic maps,timeline and website formats, each with its own presentation characteristics.

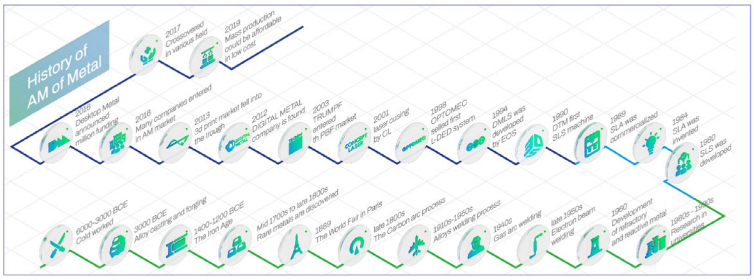
1. Gigamap: This is a confusing-looking image to better show all the technologies and their subordination, as well as some key features of comparison, this kind of the map does not have a very clear focus,but more to highlight the relationship of various technologies, help users to roughly understand all the technologies and their similarities and differences, and even visualize how to choose the right metal AM technologies for the user needs.

2. Timeline: The development of metal AM does not happen overnight, so we start our analysis from the history of the development of metal, starting from why people used metal in ancient times and how to deal with it, then we analyze several important events of modern metal processing technology, to the rapid development of modern technology and the rise of additive manufacturing in the Industry 4.0 era, to the current application of metal materials in a series of important events to better demonstrate the birth process of AM of Metal.

3. Web site: Interaction can facilitate the communication between users and information, making it easier for users to learn and use it. Besides, our project involves a lot of complex AM technologies,and the user needs to be ableto classify them in an easy-to-understand and systematic way. The main menu with split bars and the detailed labeling of specific AM technologies and interactions allow users to learn the current state of the industry and technical details of AM of Metal better and faster.

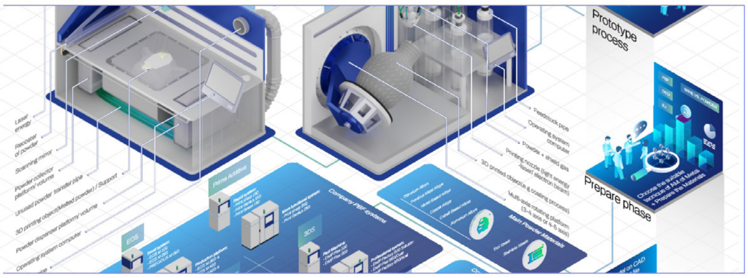


Additive Manufacturing of Metal



TIMELINE

You can see from the cold weapon age, the development of metalworking history and the time when the AM technology was invented and lastly why and how the AM of metal part appear.



GIGAMAP

Represents all the parts of AM of metal, there are 2 main categories of AM of metal, and the working flow ecc. Form the origin of AM of metal, the current statement and the development of future. For you to know the technologies and to choose a suitable one.

TECHNOLOGY DETAIL

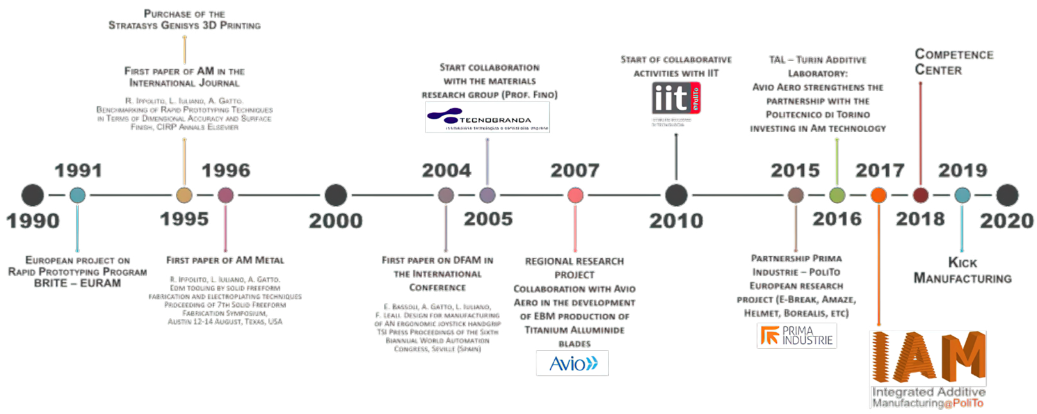
Talk about all the details of technology of any technologies in advantages and disadvantages, what's more also by using the label for sorting out for the user to choose more easier.

4.1

About IAM@PoliTo Center

1.What is IAM? What is the main business?

IAM is an integrated Additive Manufacturing Research Center, composed of professors from five departments of Politecnico di Torino, as well as 20 researchers and 20 fellows and PhD students whose mission is to create a multidisciplinary AM research platform to deal with and overcoming the open challenges in terms of machines, materials and applications, and of contributing, together with other industrial actors, in the development of a new generation systems destined for final production from the Industry 4.0 viewpoint.



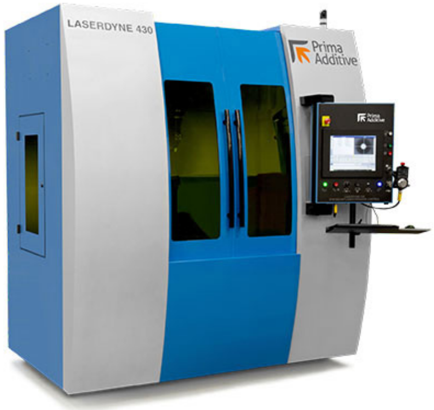
2.What does IAM of Metal have to offer?

In IAM for DED technology there is machineform **PRIMA ADDICTIVE, LASERDYNE-430**

The SLS technology is **EOS FORMIGA**.

For polymer mix materials there is **3NTR A4 V4**, **STRATASYS DIMENSION ELITE**, **F370**, **MARKFORGERD MARK TWO**.

For PBF technology there is **ARCAM A2X**, **CONCEPT LASER MLAB**, **EOSINT M270 @IIT**, **PRINT SHARP250**.



4.2
Moodboard

Mood board is a method by which artists usually find a suitable design by piling up inspirational images before creating a piece of work.

We can see AM technology represents the future trend, not only for technology, but a better method of life. So we have identified some keywords, such as technology, futuristic,sustainable, and AM, robot, multiaxis etc, all of these were linked with intelligent future.

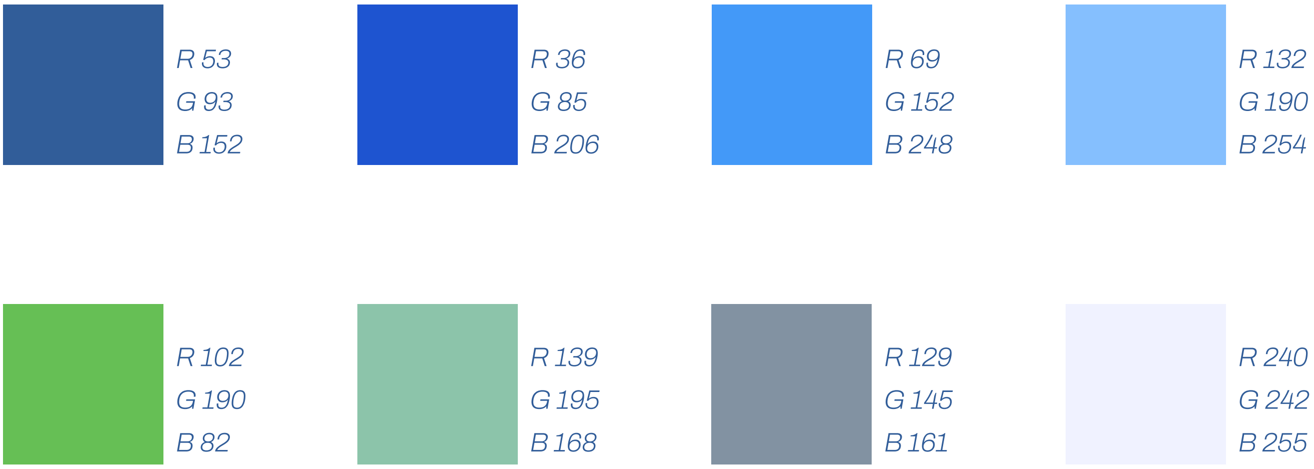
What's more, from the moodboard, we have made a colour-absorbing method for finding out the percentage of different colours in a certain extent. It can be seen that the colours corresponding to these keywords are blue, green and black,white and grey(which belong to black and white).

The final production of moodboard which is designed with two series of colours: blue and green as the base colours, blue represents more advanced technology, while green symbolizes environmental protection and sustainability, and also metaphorically represents the future development trend of AM of Metal's technology.

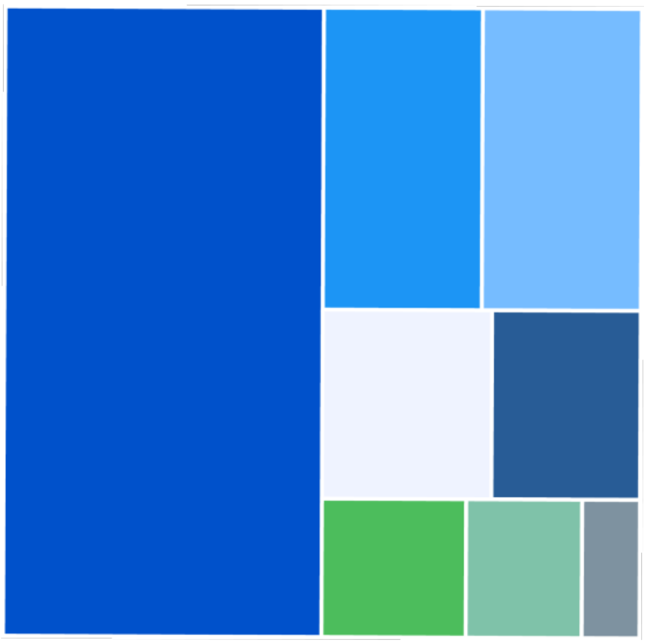
We pixelated the moodboard so that it is obvious that the color types with a high percentage of colors, blue and green, especially blue, account for more than 80% in almost every image, or even the whole moodboard, while green only plays an accent role and accounts for a relatively small percentage. By filtering and comparing we get a rectangular tree diagram of color percentages and our color palette, which will be applied to our entire project.

Based on the images obtained from the moodboard pixelization, we filtered and counted our color palette and the number of squares they occupied, and finally we used a rectangular tree diagram to show the approximate percentage of colors that reflect the different colors. With this percentage we can determine the proportion of blue and green we use in the gigamap later to avoid color imbalance problems.

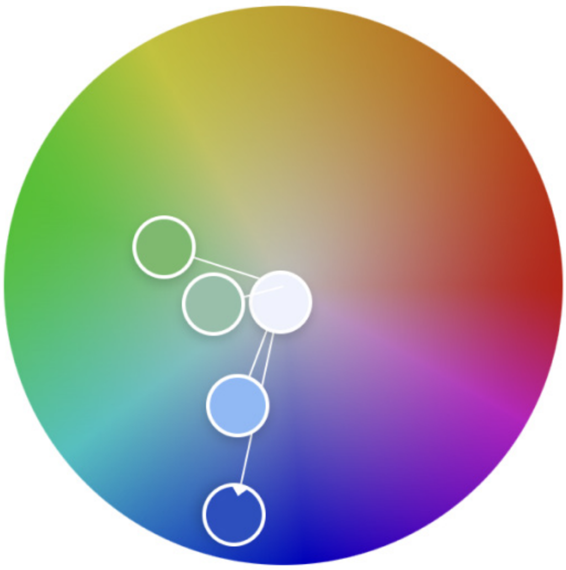
Finally, we chose two series of colors in the more typical colors, through the color ring we can clearly see that they are adjacent colors in addition to the difference in saturation. Therefore, our final color tone is mainly blue, green as a secondary, adjacent colors to make the color overlap more natural, soft changes, and then by adding different saturation, so that the color is more layered.



Color platte



Color Percentage



Color Wheel

4.3
Gigamap

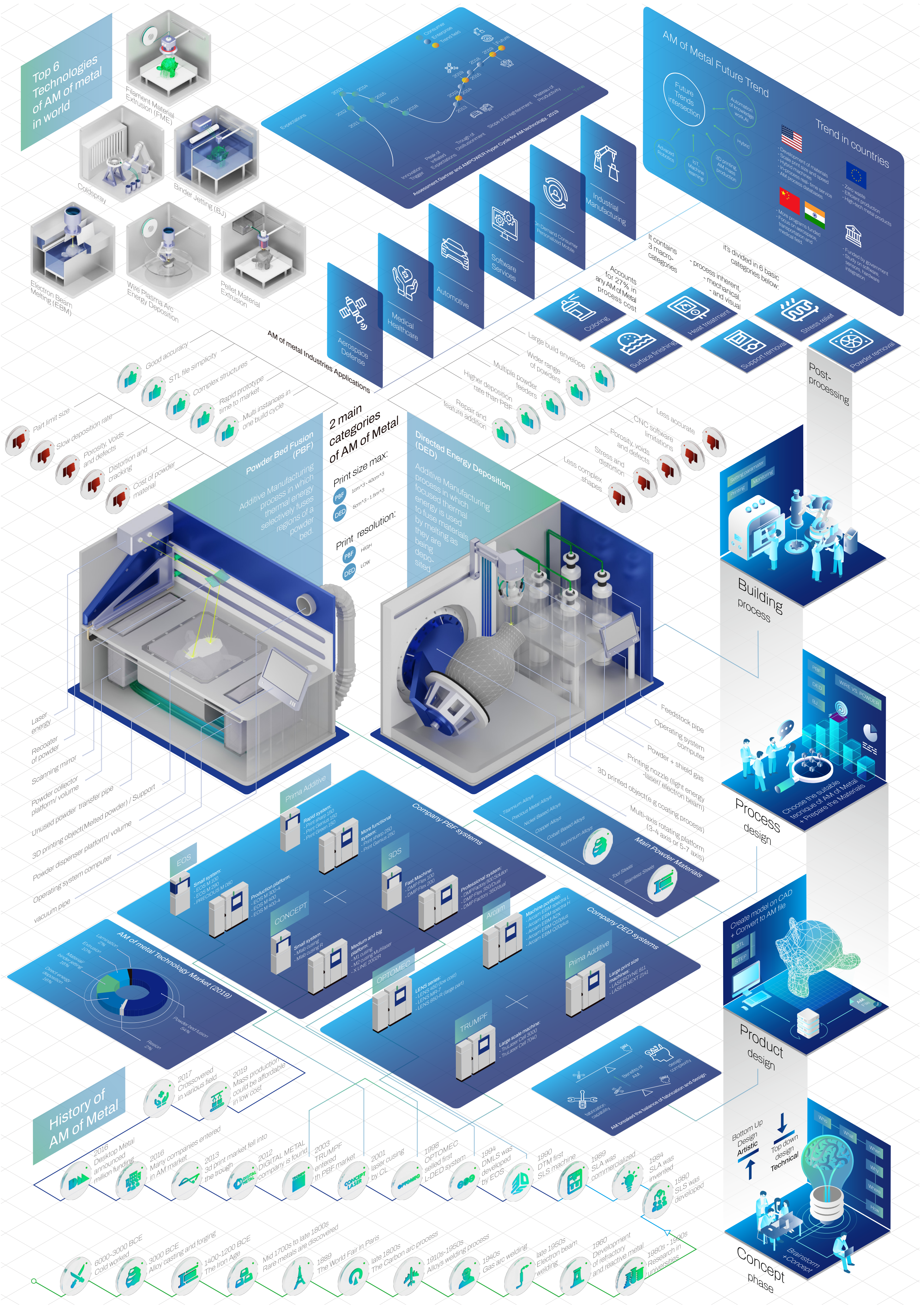
We wanted to create a comprehensive graphic map that was inherently flat and therefore lacked interactivity, so we created two maps for different purposes.

The map1 is mainly used to show the AM of Metal technology in general, including timeline and post-processing, etc.. It is suitable for a rough introduction to the user in the form of an easy-to-use map; from the bottom to the top, the historical development, the current development of metal AM (including the mainstream technologies, the companies with a large market share and, from the bottom to the top, the historical development, the current development of metal AM of Metal (including the mainstream technologies, the companies and technologies with a significant market share,and the corresponding materials, fields and machines), and the future development trend and possible new fields are shown at the top.

The map2, on the other hand, is more oriented to let the user choose the appropriate metal AM technology, shown in a concrete way the supply of different materials, the energy form, and the application areas and mainstream print sizes of the different technologies through the inclusion of relationships and colour distinctions, as well as showing the relationships between them,making it easy to compare the advantages and disadvantages of the different technologies. So it will be used on the webpages to enhance the experience through interaction.

For the presentation of complex metal AM technologies, there is a great need to use a very intuitive and unified style of image, and through our research, it is not easy to clearly explain the specific working principle and specific features of each technology through a single flat image, so we try to turn to a three-dimensional perspective, but there are also problems of perspective and scale size in three dimensions, so we should choose to use an image format that solves all of the above problems.

The 2.5D style is a trendy image creation method in the industry. The perspective is between 2D and 3D but in fact it uses an orthogonal axonometric expression to depict the object by depicting only three characteristic surfaces: the light side, the light and dark intersection, and the dark side. It can avoid the problem of inconvenience to the user due to perspective or occlusion, and has high aesthetic characteristics. However, since 2.5D style images are more complex to produce, involving the collocation of multiple facets, it is not suitable for making more complex diagrams from the principle,so we took a compromise approach by completing the 3D modelling through Blender software first, which should be kept as simple as possible, without complex surfaces. Finally, the camera is positioned from a positive perspective, rendering to get the 2.5D effect we thought.

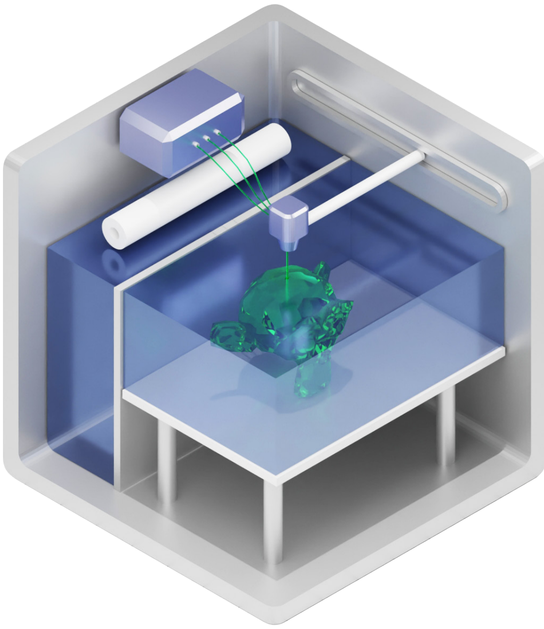


Top 6 Technologies of AM of metal in world
Filament Material Extrusion (FME)
Coldspray
Binder Jetting (BJ)
Electron Beam Melting (EBM)
Wire Plasma Arc Energy Deposition
Pellet Material Extrusion
Expectations
Innovation Trigger
Peak of Inflated Expectations
Trough of Disillusionment
Slope of Enlightenment
Plateau of Productivity
Time
Assessment Gartner and AMPOWER Hype Cycle for AM technology, 2019
AM of Metal Future Trend
Future Trends Intersection
Trend in countries
Aerospace Defense
Medical Healthcare
Automotive
Software Services
On Demand Consumer Personalized Mobile
Industrial Manufacturing
AM of metal Industries Applications
Accounts for 27% in any AM of Metal process cost
It contains 3 macro-categories
- process inherent,
- mechanical,
- and visual
it's divided in 6 basic categories below:
Coloring
Surface finishing
Heat treatment
Support removal
Stress relief
Powder removal
Post-processing
Good accuracy
STL file simplicity
Complex structures
Rapid prototype time to market
Multi instances in one build cycle
Part limit size
Slow deposition rate
Porosity, voids and defects
Distortion and cracking
Cost of powder material
Large build envelope
Wider range of powders
Multiple powder feeders
Higher deposition rate than PBF
Repair and feature addition
Less accurate
CNC software limitations
Porosity, voids and defects
Stress and distortion
Less complex shapes
2 main categories of AM of Metal
Print size max:
PBF
DED
Print resolution:
PBF HIGH
DED LOW
Powder Bed Fusion (PBF)
Additive Manufacturing process in which thermal energy selectively fuses regions of a powder bed.
Directed Energy Deposition (DED)
Additive Manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.
Building process
Laser energy
Recoater of powder
Scanning mirror
Powder collector platform/ volume
Unused powder transfer pipe
3D printing object(Melted powder) / Support
Powder dispenser platform/ volume
Operating system computer
vacuum pipe
Feedstock pipe
Operating system computer
Powder + shield gas
Printing nozzle (light energy -laser/ electron beam)
3D printed object(e.g coating process)
Multi-axis rotating platform (3-4 axis or 5-7 axis)
Process design
Choose the suitable tecnique of AM of Metal + Prepare the Materials
Company PBF systems
Prima Additive
EOS
3DS
CONCEPT
Main Powder Materials
Titanium Alloys
Precious Metal Alloys
Nickel Based Alloys
Copper Alloys
Cobalt Based Alloys
Aluminium Alloys
Tool Steels
Stainless Steels
Company DED systems
Arcam
OPTOMEC
Prima Additive
TRUMPF
AM of metal Technology Market (2019)
Powder bed fusion
Direct energy deposition
Binder jetting
Material extrusion
Lamination
Product design
Create model on CAD + Convert to AM file
STL
STEP
AM breaked the balance of fabrication and design
History of AM of Metal
2017 Crossovered in various field
2019 Mass production could be affordable in low cost
2016 Desktop Metal announced million funding
2016 Many companies entered in AM market
2013 3d print market fell into the trough
2012 DIGITAL METAL company is found
2003 TRUMPF entered in PBF market
2001 laser cusing by CL
1998 OPTOMEC selled first L-DED system
1994 DMLS was developed by EOS
1990 DTM first SLS machine
1989 SLA was commercialized
1984 SLA was invented
1980 SLS was developed
6000-3000 BCE Cold worked
3000 BCE Alloy casting and forging
1400-1200 BCE The Iron Age
Mid 1700s to late 1800s Rare metals are discovered
1889 The World Fair in Paris
late 1800s The Carbon arc process
1910s-1950s Alloys welding process
1940s Gas arc welding
late 1950s Electron beam welding
1960 Development of refractory and reactive metal
1980s - 1990s Research in universities
Bottom Up Design Artistic
Top down design Technical
Brainstorm + Concept
Concept phase

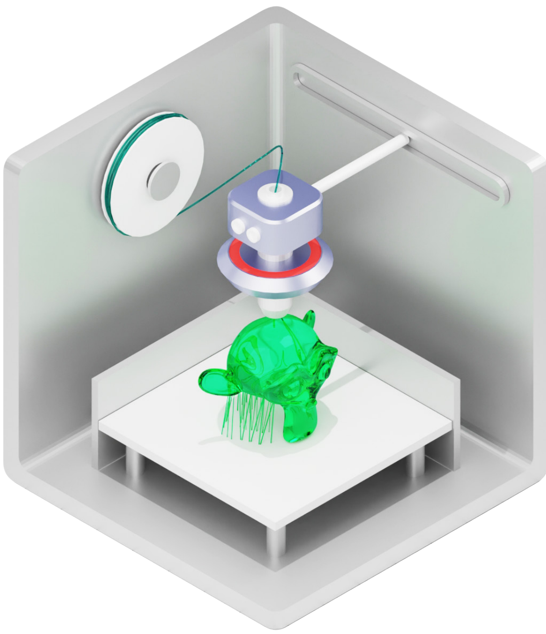
The complex and diverse AM technology, we hope to express in two ways; of course, this is based on the current market share of each technology and the degree of application to distinguish, so we finally chose a total of eight technologies to use 2.5D style,which indicates that the two major categories of PBF and DED, with a more detailed portrayal of it, the remaining six are in accordance with the most current. The remaining six are selected following the most current six specific technologies to be popular, the degree of engraving in, but still have a three dimensional sense. We also need to focus on the material, display,material colour is following mood board, especially the six specific technologies that are made in a square space 1:1:1 aspect ratio has this better aesthetic, and also with two large AM of Metal category to distinguish, highlight the subordinate relationship.

For the remaining technologies, we chose to represent them by drawing icons because of their low market share. The icon drawing process is biased towards flatness, but it also shows the difference in characteristics between technologies, and to some extent, icons are only two-dimensional, avoiding the problem of three-dimensional perspective generated by three-dimensional, and more able to highlight features.

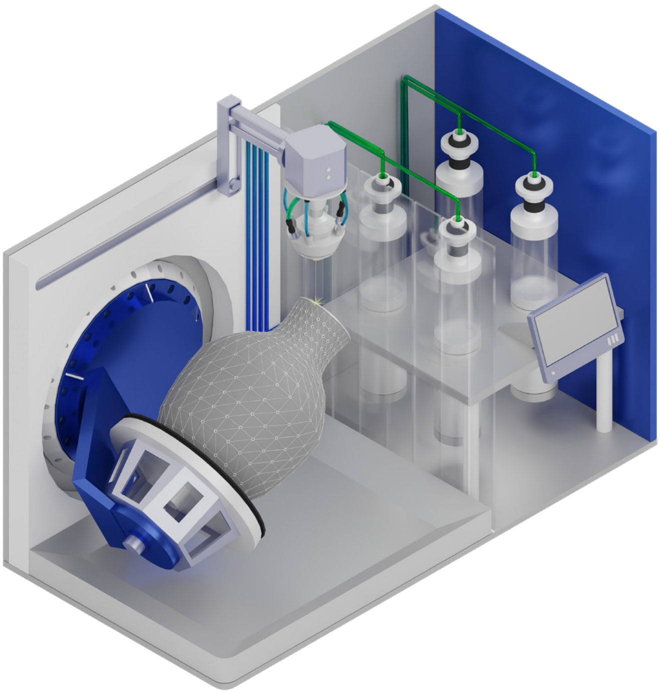
Icon mainly also needs to explain the production method, why add the rectangular box (confined space, the need to add protective gas, smaller machines),line thickness, what the type represents respectively, the size of the circle, how to use the colour, why so used, and is continuing to do.



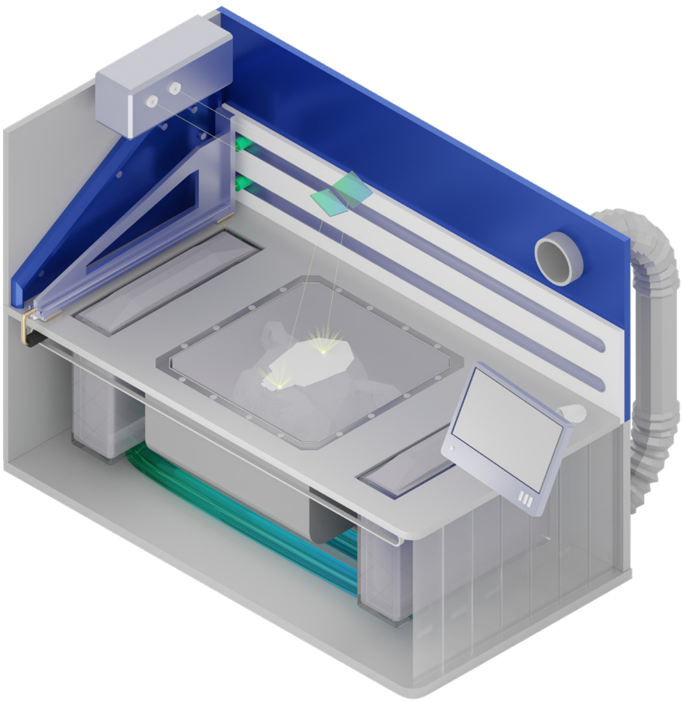
Binder jetting



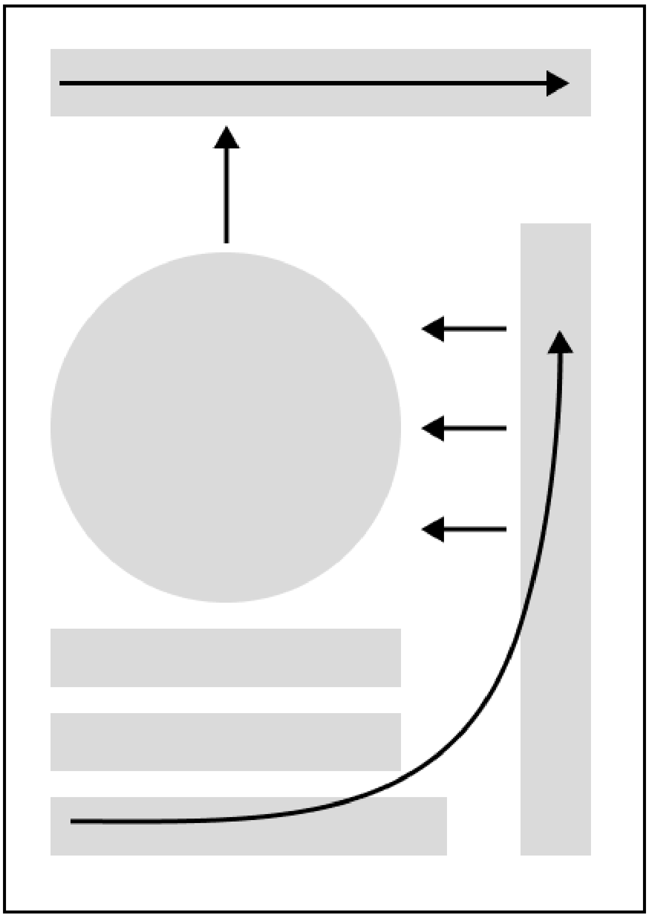
Filament material extrusion

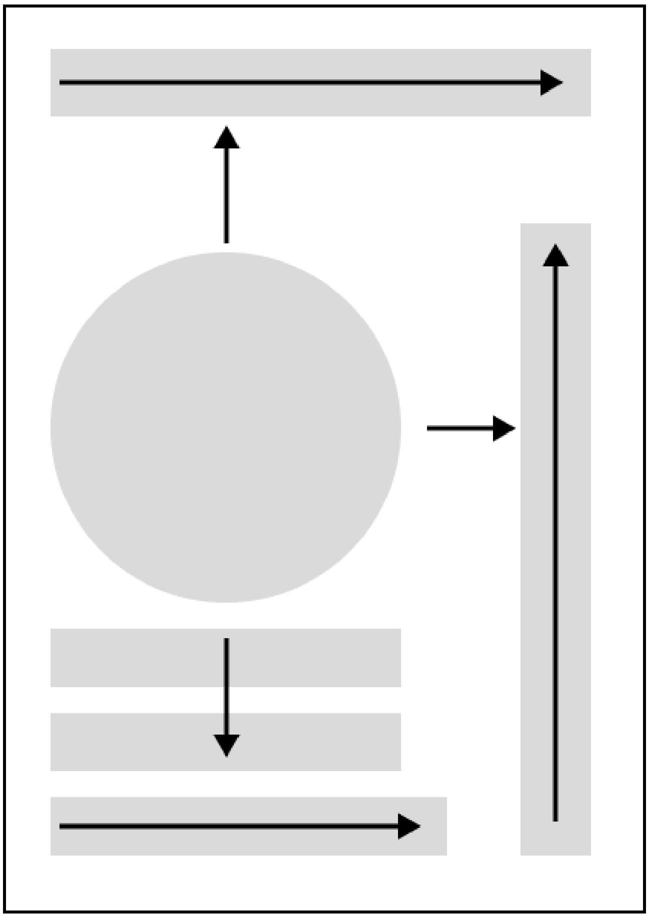


DED



PBF



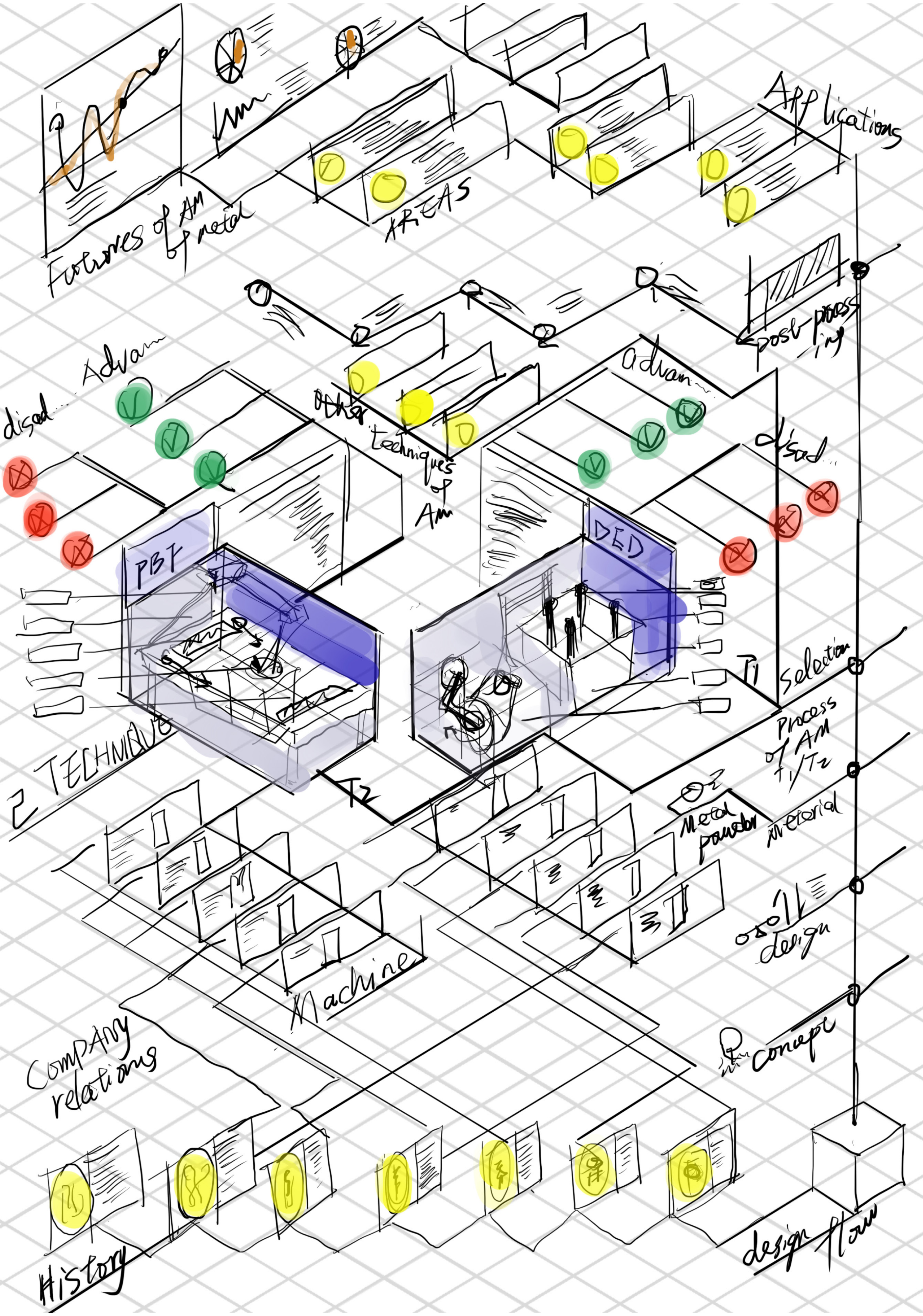


Content guidance direction

In terms of content, we start from left to right and then from bottom to top. We arrange the content into 3 stages, first the origin of AM, which is shown through Timeline, then the AM of metal stage, which is the building process, including the whole process from design to post-processing, in which we can also connect to the two main AM of metal technologies at present At the end, the future development trend of AM of metal is introduced at the top.

Visual guidance direction

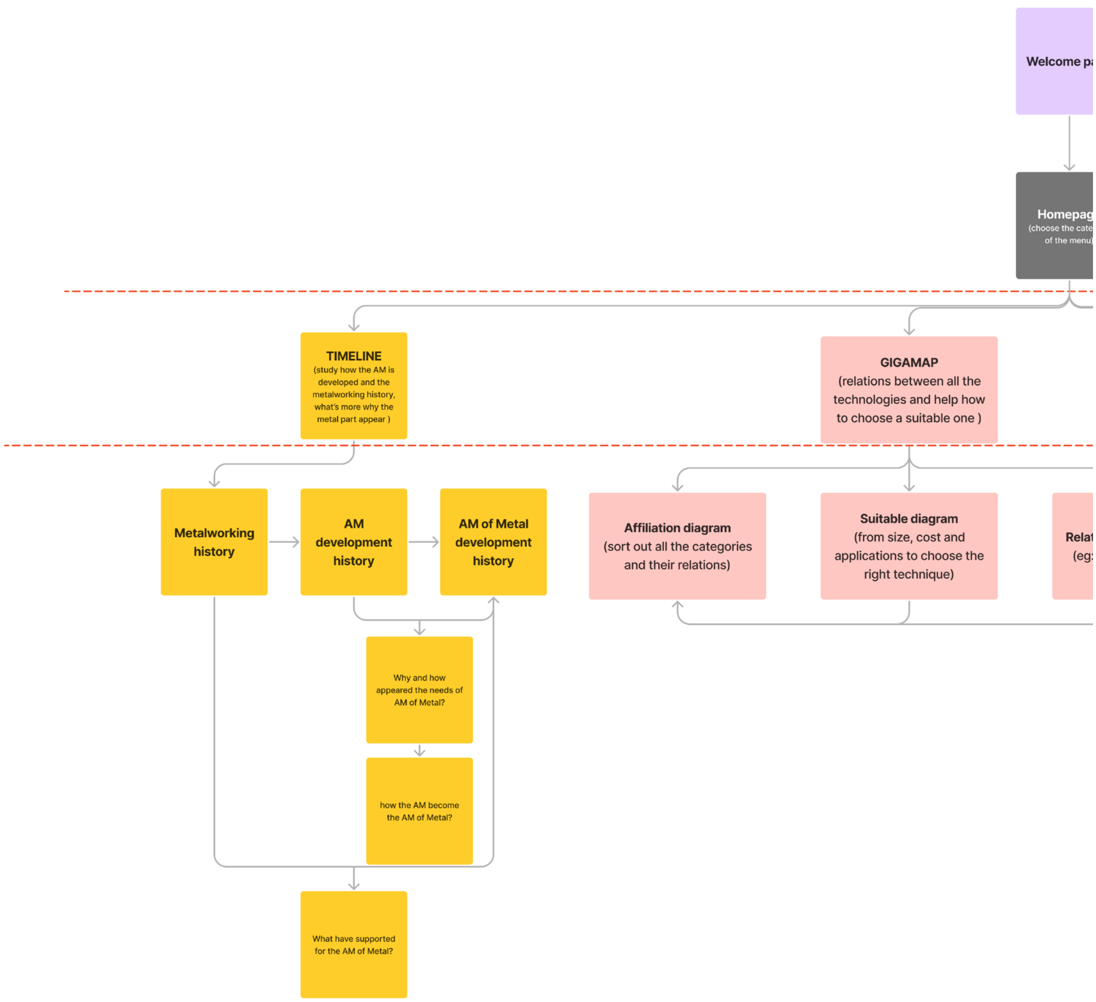
Visually, the two main types of AM of metal are used as the center, allowing users to quickly understand the industry, and then the visual disperses around, and then follow the content of each section to guide the direction to understand the other parts in detail. In general, it is a central composition, with the type as the focus, avoiding other parts to steal its visual center guidance.



Sketch of Gigamap

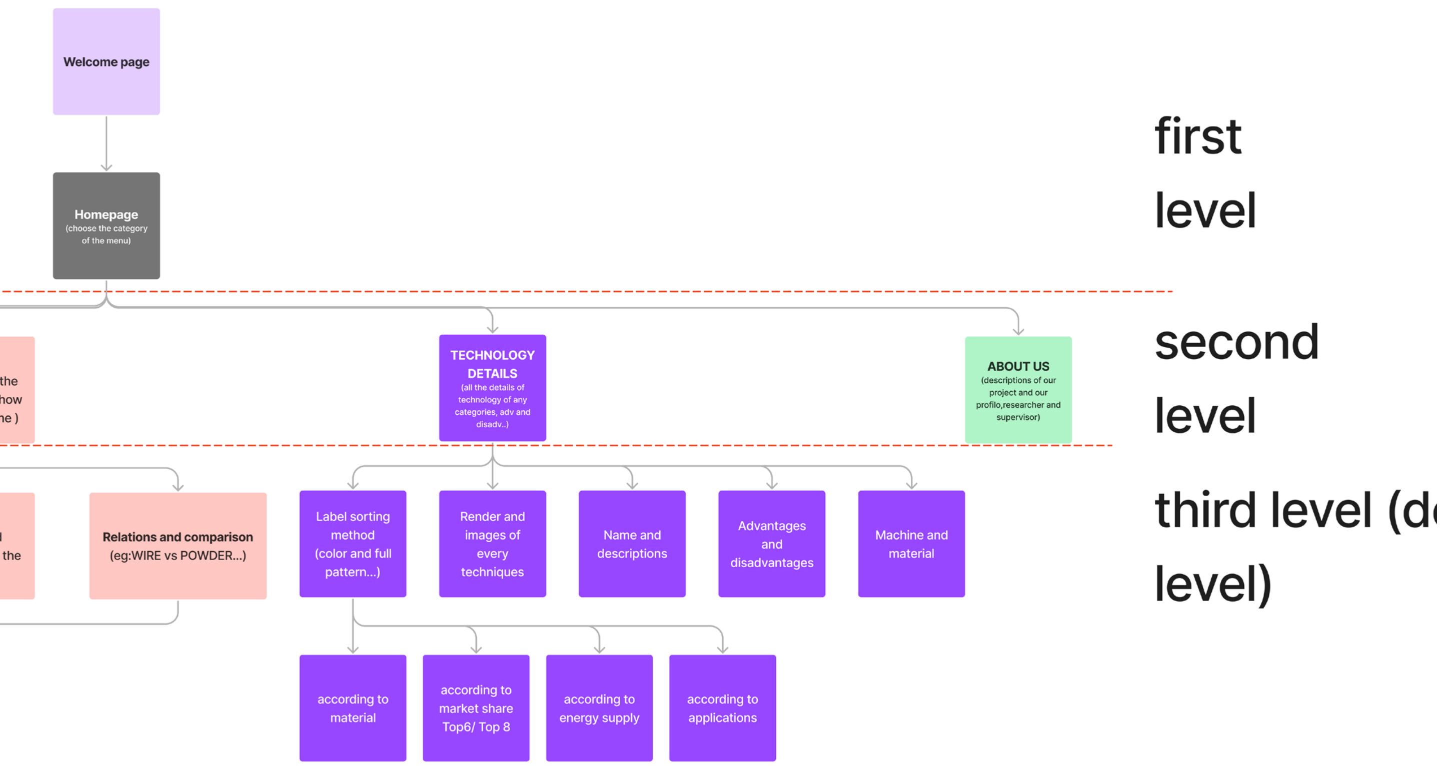
4.4
Web design

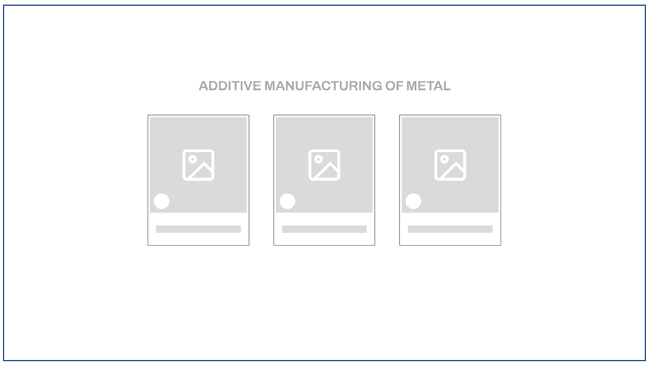
The web page is divided into three levels, starting from the SITEMAP stage.
The first level is the welcome page and the homepage, the welcome page is a circular composition to highlight the big title and the start button; by clicking the start button, the user can enter in the homepage, through the colour and circular composition to create a sense of the atmosphere; the homepage is clear and concise, there are three main chapter categories, respectively in the form of cards to show the user to provide a choice of the interval, and through the mouse hover in/out can see the change in the form of the cards to reflect theinteraction, and finally, the directionality of the head cut to guide the user to the correct page.The second level is to enter the three main partsof the page, in which each of the three pages can see the details of each part, these andall the parts that can be interacted with also constitute the third level.



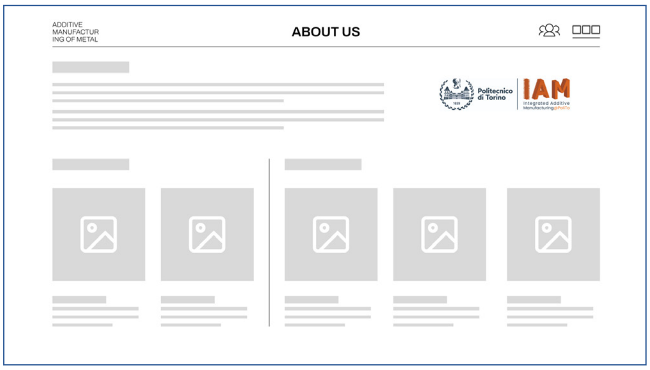
The second level can be seen as the overall overview, while the third level can provide users with more detailed content, and the meaning of each level is not the same; the overview is more intuitive to see the apparent classification differences, while details is to express the differences in more detailed content, such as operation, material differences, advantages and disadvantages, etc. We have menus on each page, a contact us button in the upper right corner, and a back-to-top button on the right. Clicking on the menu button takes you back to the homepage to select a different category, and the contact us button takes you to our profile page and introduces our projects.

WEB: https://xd.adobe.com/view/40ccbfad-37e2-4a84-8089-4b31d2d2a23a-159f/screen/237c7bca-4bbc-47e0-8fce-30dc04d3cb94?fullscreen

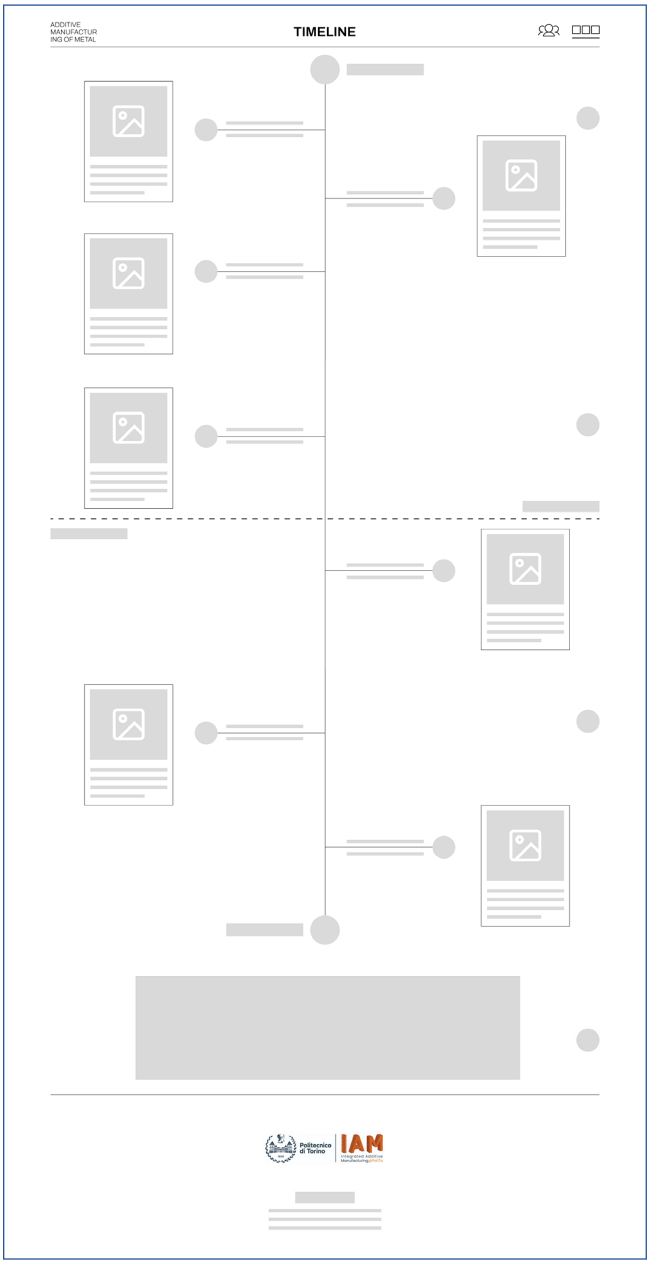




Home page

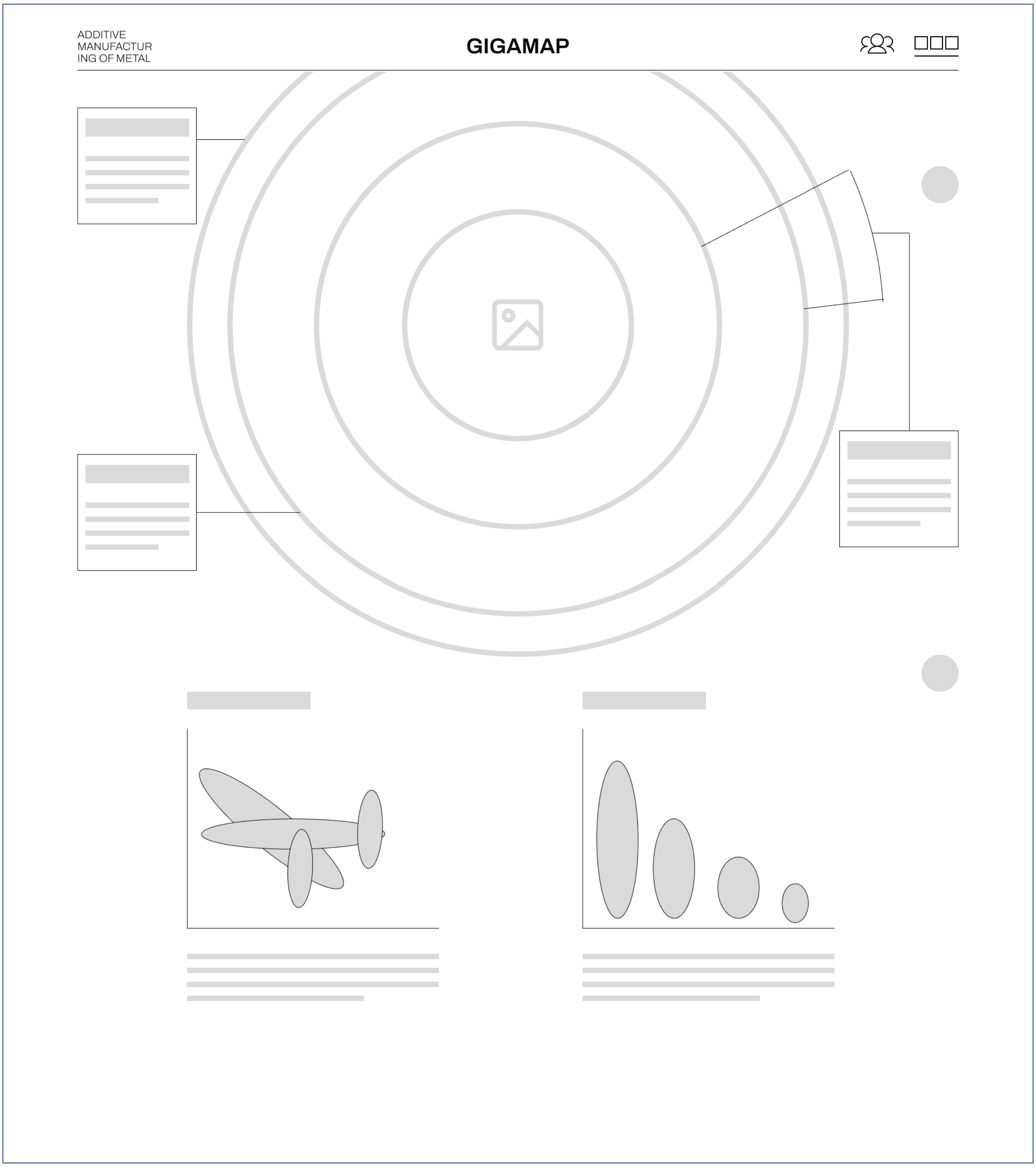


About us



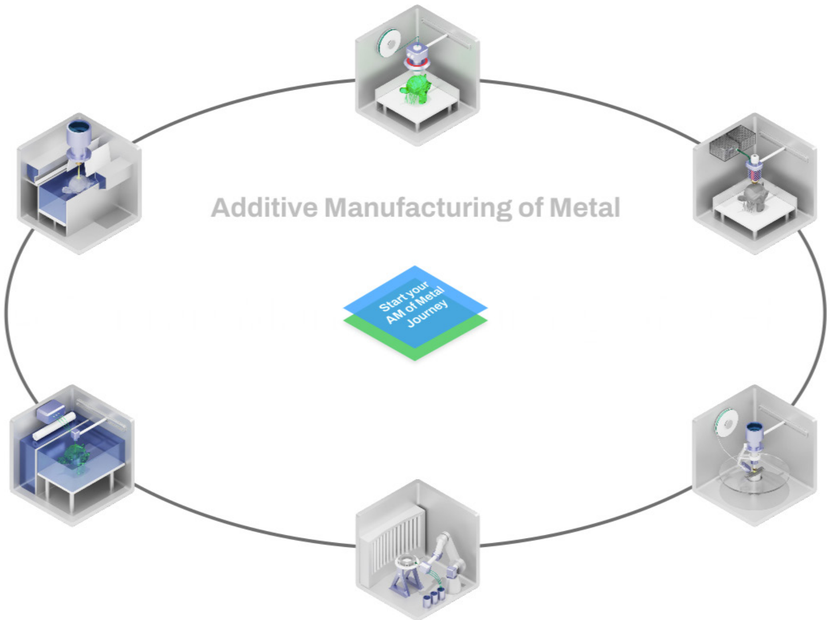
Time line

Technology details



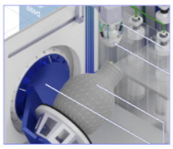
Gigamap

Additive Manufacturing of Metal

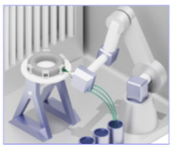


Additive Manufacturing of Metal

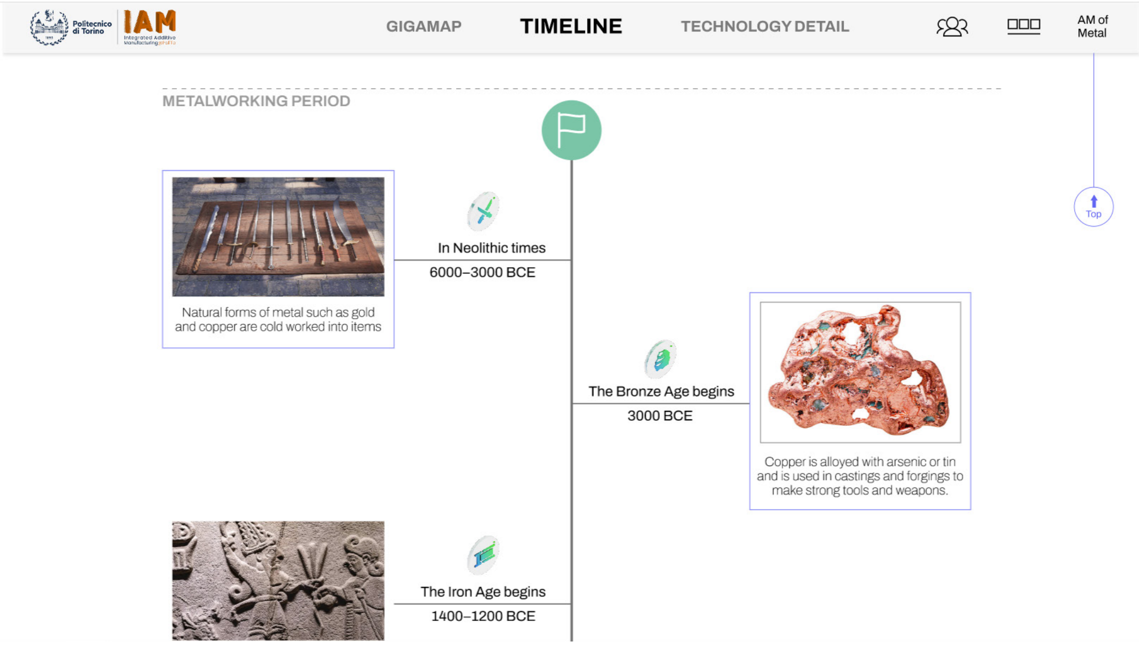
TIMELINE

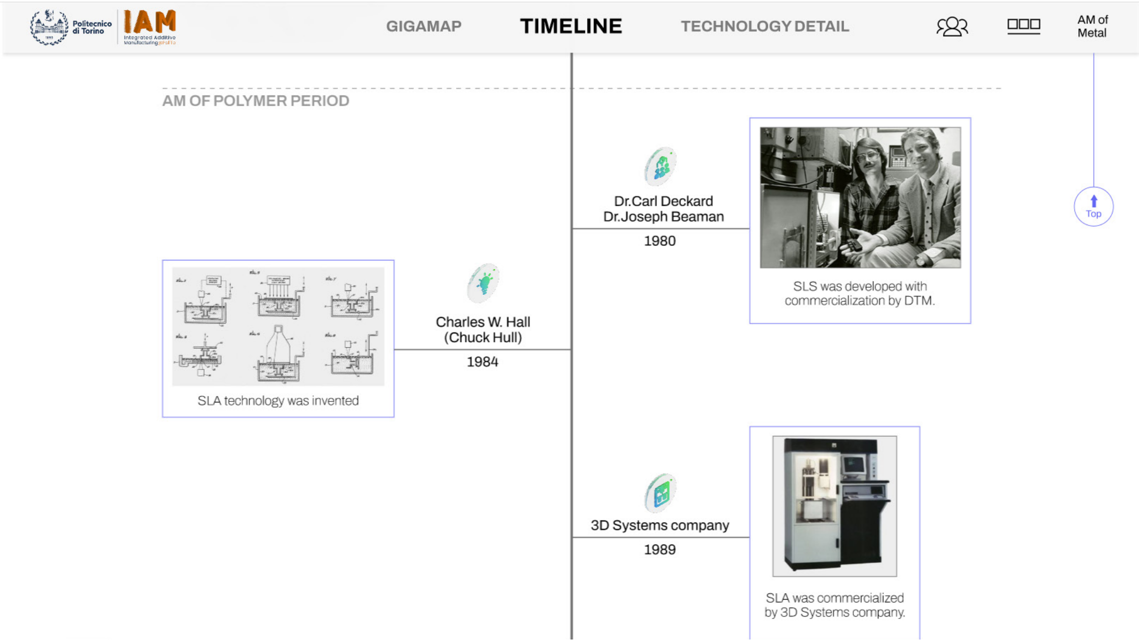


GIGAMAP



TECHNOLOGY DETAIL


Politecnico di Torino
IAM
Integrated Additive Manufacturing
GIGAMAP
TIMELINE
TECHNOLOGY DETAIL
AM of Metal
METALWORKING PERIOD
Top
In Neolithic times
6000–3000 BCE
Natural forms of metal such as gold and copper are cold worked into items
The Bronze Age begins
3000 BCE
Copper is alloyed with arsenic or tin and is used in castings and forgings to make strong tools and weapons.
The Iron Age begins
1400–1200 BCE


Politecnico di Torino
IAM
GIGAMAP
TIMELINE
TECHNOLOGY DETAIL
AM of Metal
AM OF POLYMER PERIOD
Top
Dr.Carl Deckard
Dr.Joseph Beaman
1980
SLS was developed with commercialization by DTM.
Charles W. Hall
(Chuck Hull)
1984
SLA technology was invented
3D Systems company
1989
SLA was commercialized by 3D Systems company.


Politecnico di Torino
IAM
GIGAMAP
TECHNOLOGY DETAIL
TIMELINE
AM of Metal
Label
PBF CATEGORY
DED CATEGORY
OTHER CATEGORY
TOP 6 TECHNOLOGIES
WIRE
POWDER
OTHER FEEDSTOCK
HEAT
LIGHT
OTHER ENERGY
Direct Energy Deposition (DED/ L- DED)
Category/ Techonology
DED is a 3D printing method which uses a focused energy source, such as a plasma arc, laser or electron beam to melt a material which is simultaneously deposited by a nozzle. As with other additive manufacturing processes, DED systems can be used to add material to existing components, for repairs, or occasionally to build new parts.
The DED process includes:
- Laser Engineered Net Shaping (LENS)
- Direct Metal Deposition (DMD)
- Electron Beam Additive Manufacturing (EBAM)
- Directed Light Fabrication
- 3D Laser Cladding etc.
Labels
Top
Advantages and limitations
- For complex geometries
- Reduces the material waste
- In-situ alloying
- Possibility of deposit functional and graded materials
- DIstortions, porosity
- Low part quality and accuracy
- Residual stresses and anisotropy
- High cost of raw materials
-High production times
Gallery

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