3D Printing of Metals

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Abstract of the Thesis

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Additive manufacturing (AM), widely known as 3D printing, is a manufacturing method that produces parts from powders layer by layer. Many techniques have been developed to achieve this. In this thesis, the historical development and general principles of additive manufacturing are covered. The techniques for producing metal parts are explored, with a focus on the defects, processing parameters, mechanical properties and the relationships between them and the influences on each other. The various metal AM techniques are compared with the analysis of their strength, limitations and applicable conditions. The applications and mechanical properties of the most studied metal/alloys is another focus. Currently only a few metal parts are commercialized, however, due to the high potential and the advantages in many high end areas, the research activities and the recent efforts could act as a roadmap for the development of ongoing AM new materials and the improvement of present day AM process techniques.

Key Words: **Additive Manufacturing, 3D printing, Metals/alloys, Selective laser melting, Mechanical properties**

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List of Abbreviations

AM	Additive Manufacturing
CAD	Computer Aided Design
STL	Stereolithography
SLS	Selective Laser Sintering
SLM	Selective Laser Melting
PBF	Powder Bed Fusion
DED	Direct Energy Deposition
LENS	Laser Engineered Net Shaping
EBF	Electron Beam Fabrication
LOM	Laminated Object Manufacturing
UAM	Ultrasonic Additive Manufacturing

Chapter 1 Introduction

1.1 Motivation

3D printing, or Additive Manufacturing (AM), is a key emerging technology identified by the European Union. 3D printing could potentially revolutionize the manufacturing industry by cheap manufacturing, quick production, less materials waste and able to fabricate components with complex structure. AM technologies build near net shape components without the need for machining. Therefore, AM technologies could enable the novel/complex product designs that could not be fabricated through the conventional subtractive processes and extend the life of in-service parts through repair technologies.[1]

AM Printable materials including polymers, composites, ceramics, and metals/alloys.The AM technology benefit across a broad spectrum of applications in aerospace, medical, automotive, jewelry, sculpture/design, architecture, fashion and food.

There is a great interest and activity going on for 3D printing of metals despite the majority ongoing 3D printing material systems are based on polymers. The fact that 3D printing could potential fabricate net or near-net shape high-performance metal components and thus reduce the overall manufacturing cost is attractive, especially in the area of aerospace and medical applications.

The aerospace sector is one of the areas to adopt 3D printing technology early. Due to the importance of aerospace, the R&D in 3D printing is demanding and high-standard. High-profile users include Boeing, Airbus/EADS, General Electrical Corporation. The aerospace industries could benefit from complex geometries and fabricated materials distribution such as deposit conductive materials.

The medical sector is also an early adopter of 3D printing and with a huge potential for growth. This is because the personalization capabilities of additive manufacturing and its ability to improve people's lives as the materials used and the processes optimized to meet the criterion of medical area. For those who needed, organs, bones, teeth could be printed. In 2002, the first functional kidney was printed; in 2008, the first prosthetic leg was printed.

Hence, the objective of this project is to advance the fundamental understanding of the methods and parameters of 3D printing metals, printing and manufacturing processes, the mechanical properties of fabricated products in order to enable high quality, low carbon footprint and provide economic solutions that can fit the needs of 3D printing manufactures. Perspective on future research development will be discussed.

1.2 Definition and Characteristics

3D printing, or Additive Manufacturing (AM), was defined by American Society Test & Manufacturing as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive techniques, additive laser manufacturing, laser manufacturing, and freeform fabrication".[2] This definition applies to all types of materials including metals, polymers, ceramics, composites, biological and food materials systems.

In contrast to traditional subtractive manufacturing, 3D printing technology is additive manufacturing based on 3D models and additive manufacturing has many benefits.

- Shape complexity

  Traditional manufacturing methods depend on moulds and cutting technologies to produce a finite number of shapes and structures. For complex hollow ones, they need to be created from several parts and assemble together. But in 3D printing robot could build complex figures as long as the structure is designed. Complexity would influence the shape in additive manufacturing. Since the product is printed layer by layer, the cost and time it takes to produce a complex part is essentially the same as that for a simple one.[3] For areas such as medical implants, 3D printed jewelry, there are many potentials.

- Functional complexity

  With the AM technologies, it enables the embedment of components like sensors, actuators, and deposits conductive materials. In the sustainable energy area, components such as heat exchangers, condensers could be designed with complex shapes to promote efficiency. In the biomedical area, shapes of implants are complex and customized, and they may take the advantage of embedding functional components.

- Materials and property tailoring

  Materials and processed could be tailored at one specific layer or point. It is possible to manufacture components with complex compositions and different property requirement of property.

- Time efficiency

  For complex part, they could usually be produced using AM technology with less time. Printing from CAD models, this could reduce the cost and time, and even have a huge impact on the storage, supply chain and assembly.

- Less human labor is involved.

  It is the printing robot build the components layer by layer based on the file data. The near-net shape components produced by AM technology would requires less post-processing.

- Less waste &less impact on environment

Less materials are wasted or need to be recovered, which has a lower impact on environment and reduced the cost. For example,

- Accessibility

  As the expanding of 3D industry, people have more accessibility to the 3D printers. Printing one's own objects might be a valuable experience. This helps to boost the 3D printing industry as a whole.

- Personized & innovation

  Due to easy access to 3D printers, people can design their own components and print out in hours. This is something unique. And they could get feedback from the printed objects. If not satisfied, they can refine the model and reprint with less cost and time. That's the same case with industry designers. This could encourage innovation and hands-on experience for both industries and common people.

1.3 Historical Development

3D printing technologies were first proposed in the 1980s, during which time they were called Rapid Prototyping. The first patent was issued to Charles Hull for inventing stereolithography (STL), a process to making polymers harden under ultra-violet light and setting up the apparatus for making an object by layer deposition. The first object that he built was a cup of 5cm tall and it took him months to fabricate it. Two years later, Hull co-founded 3D Systems Corporation- one of the largest and most prolific organizations operating in the 3D printing sector today.[4]

Other 3D printing technologies and processes also emerged during those time. At the end of 1980s, the Laminated Object Manufacturing (LOM) technology was developed. In this method, originally patented by Michael Feygin, layers of adhesive coated paper, plastic, or metal laminates are successively glued together and cut to shape with a knife or laser cutter. But the applications were not particular successful over the years. Another technology for 3D printing, which is called Selective Laser Melting (SLS), was invented at the University of Texas at Austin. This consists of melting particles of powder by a laser beam.[4] The patent was issued to C.R. Deckard in 1989. The University of Texas formed the first SLS company and it was renamed DTM Corp., which started to build commercial machines cooperating systems and acquired it in 2001. The invention of SLS technology spawned the additive manufacturing industry.

The advent and popularity computers and the availability of industry lasers are critical to the development of 3D printing technology. In the late 1980s, the AM processed include but are not limited to selective laser sintering. Over the next coming twenty years, the research has been done utilizing those processes to solve the research problems and develop new techniques in multiple areas including aerospace, automotive, biomedical, energy and consumer goods. The impact of AM continues to grow in terms of the parts fabricated, the machines sold and patents and papers published.[5,6]

In 2005, the goal of offering individuals low-cost, office- and user-friendly systems initiated the large expansion of 3D printing industry. At the beginning, up to the early 2000s, the 3D printing was high-end and expensive systems, which were applied towards the productions of high value, highly engineered, complex parts in areas across aerospace, automotive, medical and fine jewelry. This is still ongoing and growing. To facilitate the lower end of the market, a project called RepRap (Replicating Rapid Prototyping) was launched. RepRap was the first of the low-cost 3D printers, and the RepRap project started the open source 3D printer revolution. RepRaps print objects from plastics. Software and hardware are open-sourced.

Based on the RepRap project, the MakerBot Industries were established in 2006 to provide do-it-yourself kits for anyone with just basic technical skills. The open-source revolution produced a sort of large diffusion and democratization of additive manufacturing so that people could afford to create objects by their own.[4]

1.4 General Principles

The 3D printing process starts with modelling. The models of the components can be draw with a computer aided design (CAD) system. The design is created by designed based on the requirement of the objects. The CAD file is later converted to a STL file. If have a real world object, the models could also be constructed via a 3D scanner. The models created with CAD has less errors and are flexible with making changes before printed.[7] CAD has world-wide usage and it is user friendly and compatible. These are the reasons for using CAD for modelling. Then the model is electronically sliced by soft wares such as Slicer, Magics to generate lines data which represent the robot path to make this component. Fig.1.1[8] shows a sequence of drawing for a simple component and its resulting slices. After the slices are generated, a G-code file containing instructions on how the machine tools make the component is produced. The G-code file is tailored to specific 3D printers and then could be printed using the printing client software.

The second step is printing. Despite printing methods varies due to the materials used, the building process is layer by layer until the whole component is built. Typical layer thickness is around 100 μm, though some machines could print layers as thin as 16 μm. Describing the thickness of layer and X-Y resolution is called printer resolution in micrometer or dots per inch. The diameter of particles are about 50 to 100 μm.

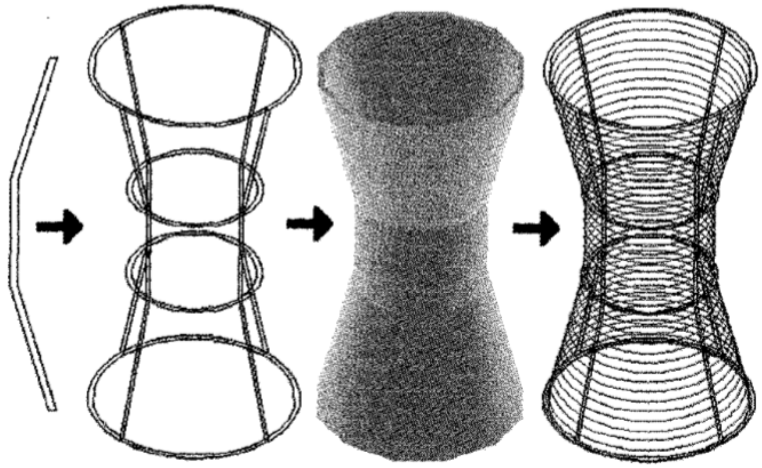

Fig. 1.1 3D model and slices of a component

(From left to right) Cross section drawing, its orthogonal view, final solid shaded, solid model with resulting slices[8]

The resolution of printer-produced component is sufficient in many applications. However, if high resolution is required, printing a slightly oversized version of the goal object and then, removing extra material with a higher resolution subtractive process could achieve better resolution. For instance, printable polymers Acrylonitrile Butadiene Styrene, is able to allow the surface to be improved using chemical vapor process.

1.5 An overview of additive Manufacturing Processes

There are workshops held to develop and articulate the roadmap for research in the area of additive manufacturing. In 2009, the Roadmap for Additive Manufacturing Workshop was held at NSF Stafford Building. In 2012, the Roadmap Workshop on Measurement Science for Metal-Based Additive Manufacturing was held at the NIST campus in Gaithersburg, Maryland. According to those two workshops, AM processes involving design and analysis, process and machines, materials and materials processing, process control, supply chain capabilities.

Design should be the first step of 3D printing. CAD software is widely used for designing models. Before the models are printed, analysis is important to ensure that the component won't break and meet the requirement of mechanical properties after printing. Analysis should detect problems in the current model and provide a visualization to users so that the users can fix them. Several approaches like simulation-based analysis, pure geometric approaches have been formed to predict the fragile area. Zhou et al. perform worst-case structural analysis under load and predict fragile areas by running the model analysis.[9] The geometric approach relies on medial axis transformation, which approximates the shape with tangent spheres, to estimate the minimum thickness.[10]

There are a variety of processes for the additive manufacturing of metals. Accordingly, the machines used differs in principal, hardware and set up and this influences the property of components. It is going to be covered in next chapter. To better capture the complexity in the multiple interacting physical phenomena, a better understanding of the basic physics of AM processed is needed.

Raw materials characteristics, such as powder size, size distribution are important to the AM product quality. Therefore, improvements to feedstock materials or development of new materials could have direct impact on AM technology.[11] To design new materials and better utilize AM techniques, it is necessary to acquire a comprehensive understanding of the materials property that affect the micro-structure. The new high-temperature alloys with faster solidification rates is a good example. Better understanding of AM material properties, characteristics could improve the ability to design new materials and products. It also enables better control of AM process and the enhancement of the quality of final products.

In terms of process control, closed loop control has great advantage in measuring in-situ material properties, enabling the control over the microstructure of materials, and allowing the prediction on components properties. By providing the feedback of the process and in-situ measurement, materials defect such as residual stress, distortion could be decreased and thus, the product quality is improved.

The availability of reliable, consistent metal powders is essential for high-quality AM products. Developing new methods could be one approach to increase the availability of metal powders. The recycling and reusing of AM materials is also an important way for supply.

Chapter 2 An Overview of Additive Manufacturing Processing Techniques of Metals

A number of additive manufacturing techniques of metals are available today. Each technique has its own strength, challenges and unique uses. AM systems could be categorized by the material feed stock, energy source, build volume, the way the material is joined, for instance using a laser etc. In this chapter, each technique and category is explored. The strengths and weaknesses of each method is discussed. The primary focus would be powder bed fusion and direct energy deposition due to the large volume of publications about those processes, which will be discussed in more detail in next chapter.

In terms of feedstock, AM systems could be divided into three categories: powder bed system, powder feed system, wire feed system.

2.1 Additive Manufacturing Systems

(i) Powder bed systems

Almost all powder bed systems use a powder deposition method consisting of a powder spreader to spread a powder layer onto a substrate plate and a powder reservoir. Powder bed additive manufacturing uses fine powders ranging from 5 to 50 μm to build parts layer by layer. As shown in Fig. 2.1[12], a schematic of generic powder bed system, the machine comprises of a powder supply, a powder delivery system, a fabrication powder platform, a laser, a scanner system, a pointing and focusing system. First, the powder spreader spreads a thin layer of powder on the fabrication platform. The energy source could either be a laser beam or electron beam. The beam is programmed to deliver energy to the bed surface to sinter/melt metal powders to desired shape. When one layer is complete, the build platform is moved downward by one layer and a new layer is spread on the previous layer. The melting/sintering process is repeated until a solid dimensional component is completed. After complete, the un-melted/un-sintered powder could be recycled and used again. The component is heated if necessary and removed from the platform.

In general, the build volumes of those systems are less than 0.03 $m^{3.}$ The advantage of this system are its capability to print high-resolution products and maintain control over dimensions. All the powder bed manufactures are located outside of the United States. The only powder bed electron beam system, ARCAM A2, is manufactured by ARCAM, a Swedish company[13].

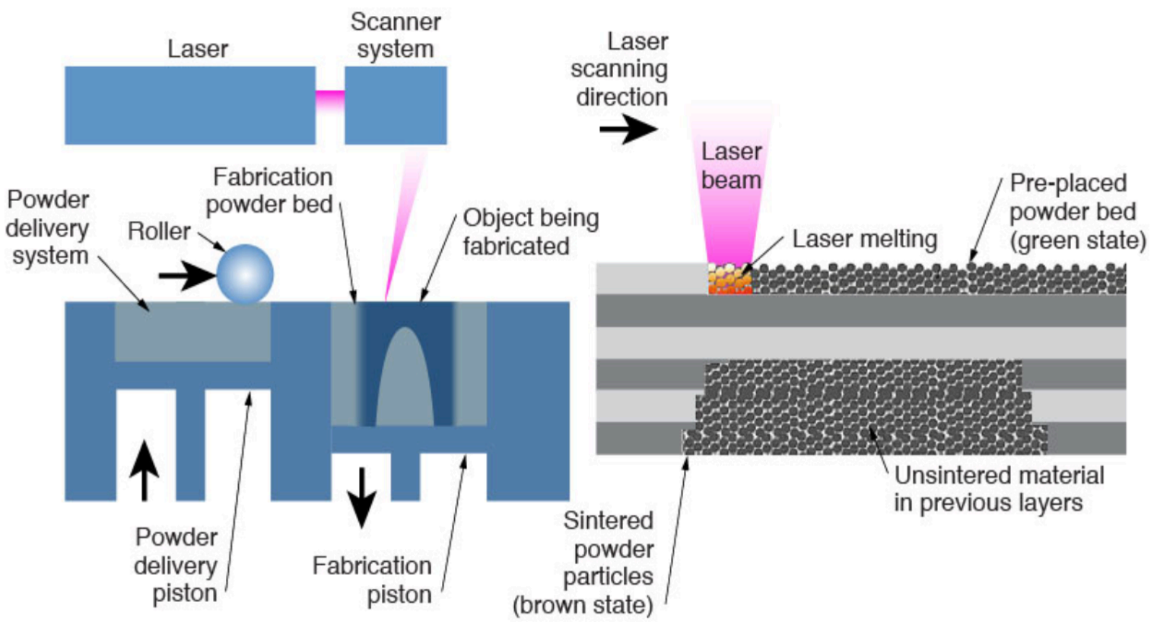

Fig. 2.1 An illustration of AM powder bed system. Image courtesy of Karma DL 1.1[12]

ARCAM A2,[14] with some parameters provided, is used as an example to illustrate the powder bed system with electron beam as the power source. Fig. 2.2 shows the outlook of the ARCAM A2. It is designed for production of any function part within aerospace industry. The components are built up layer by layer of metal powder melted by electron beam. The beam power has adjustable range from 50 to 3500 W. The beam spot size is 0.2 mm-1.0 mm. The electron beam provides high energy to melt metal powders allowing high melting capacity and productivity. The components are built in vacuum at elevated temperatures that could relieve the internal stress of the metal parts and thus, the metal parts have better properties that cast and comparable to wrought materials. The build tank volume is 250×250×400 mm. The model to part accuracy is 0.13 mm for short range and 0.20 mm for long range.[14]

Fig. 2.2 The outlook of ARCAM A2. Image courtesy of Arcam Company.[14]

(ii) Powder feed system

A generic illustration of powder bed system is shown in Fig. 2.3[13]. The powder fees system consists of a laser used to melt powders, a beam guidance system, a lens, a carrier gas to provide protection to metal parts in elevated temperature, a powder supply, a deposition head to feed metal powders, a work piece where the metal components are fabricated. Metal powders are conveyed through the deposition head onto the build surface. A laser is used to melt the metal powders layer by layer to form the desired shape. This process is repeated until the component is formed. There are two types of systems in the market. One is the deposition head is fixed while the work piece moves; another type is the work piece keeps stationary while the deposition head moves. Those two types could deposit metal powders evenly on the work piece.

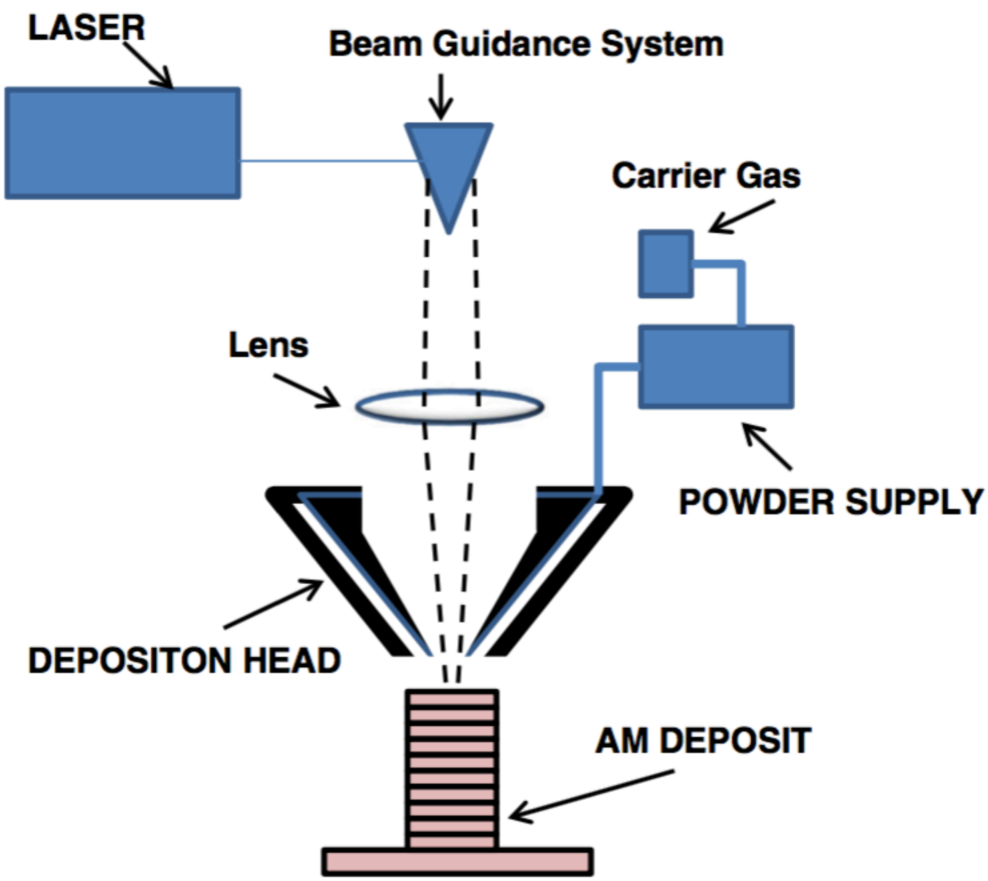

Fig. 2.3 General illustration of an AM powder feed system [13]

The advantages of this system are the build volumes of the powder feed systems are generally larger. Compared with the powder bed systems, the powder feed systems are more readily to build the volumes scale up. It can be used to repair worn or damaged component.

For example, the OPtomec LENS 850-R unit, the build volume is more than 1.2 m^3. The outlook of the OPtomec LENS 850-R system is shown in Fig. 2.3 OPtomec LENS 850-R unit is the state of art additive manufacturing system, using alloys to restore the functionality of high value metal components. It offers a large working volume, 900 × 1500 × 900 working volume, making it convenient for the modification of large industrial components and repair. The OPtomec LENS 850-R utilizes 1 or 2 kW IPG fiber laser to build up structures from metal powder one layer at a time. The motion velocity is 60mm/s. The position accuracy is within o.25mm. The linear resolution is 0.025mm. The resulting material has mechanical properties that could be equivalent to even better than the original component. The 850-R offers a full range of feature, including the closed-loop control to provide comprehensive feedback and process control, 5-axis motion to make rotary and complex repairs possible and full atmosphere control. The OPtomec LENS 850-R unit has been used to fabricate defense housing, repair compressor blade, make exhaust duct. [15] Fig. 2.5 shown the impeller repaired by the LENS 850-R system.

Fig. 2.4 The outlook of the OPtomec LENS 850-R system[15]

Fig. 2.5 Impeller repaired by the LENS 850-R [15]

(iii) Wire feed system

A general illustration of an AM wire feed system is shown in Fig. 2.6[13]. The energy source for the systems could be electron beam, laser beam or plasma arc. A single bead of material is deposited and subsequent passes is built upon to develop a three dimensional structure.

The strengths of wire feed system are they have large build volumes and are suitable for high deposition rate processing. But the resolution of the fabricated component is not as high as the other systems. So the products usually required more finishing and machining.

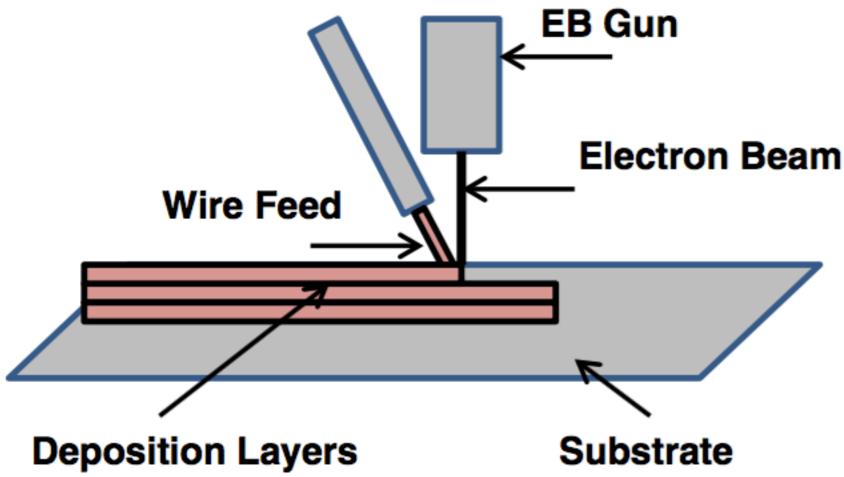

Fig. 2.6 A generic illustration of an AM wire feed system [13]

In summary, there are various type of AM systems available in the market. They could be broadly categorized into three types: powder bed system, powder feed system, wire feed system. They have distinct strengths and weakness and could be applied upon the requirement of the components such as in repair/replace parts of the expensive metal structures, the resolution of the parts, small/large part fabrication, high rate processing.

2.2 The Classification of Technologies

In 2012, the ASTM F42 Committee on Additive Manufacturing has issued a standard on process terminology to discuss the distinct classification of AM technology and machines.[16] Among the seven F42 standard categories, three categories don't apply to metal manufacturing technologies: material extrusion, material jetting and vat photo-polymerization. The following four categories are applicable to metal AM:[16,17]

- Powder bed fusion(PBF)
    - Selective laser melting (SLM)
    - Selective laser sintering (SLS)
    - Electron beam melting (EBM)
- Direct energy deposition (DED)
    - Laser beam vs. electron beam
    - Wire feed system vs powder feed
- Binder jetting
    - Infiltration
    - Consolidation
- Sheet lamination
    - Ultrasonic additive manufacturing (UAM)

(i) Powder-bed fusion

PBF includes all processes where focused energy (electron beam or laser beam) is used to selectively melt or sinter a layer of a powder bed.[17] In SLM, Metals are fully melted rather than sintered. SLS is a relatively new technique. For metals, melting is more often used instead of sintering. So SLS technique will be briefly explored. The main focus is SLM and EBM processes and their common points and differences will be discussed.

A . Selective Laser Melting

Selective Laser Melting is a particular rapid prototyping, or AM technique designed to use high-density laser to melt and fuse metallic powders. This technique has been proven to produce near net-shape parts up to 99.9% relative density.[18] This process enables the fabrication of near-net shape and near full density functional parts and has important economic benefits.

The SLM process has some common physical phenomena associated with AM technology. It is a powder bed fusion process that uses high energy laser to selectively melt metal powders layer by layer, according to the CAD file. Before the CAD data was uploaded to the SLM machine for print, the CAD file need to be converted to a STL file to generate slice data for laser scanning on each layer. The concept of SLM process is shown in Fig. 2.7[18], the building process starts with laying a thin layer of powders on the substrate plate. The laser is used to melt the metal powders according to the CAD data. Then a second layer of powder is deposited on the substrate. The process repeated until the part is fabricated into the desired shape. The loose powders are removed and recycled and the finished part is removed from the substrate either manually or by electrical discharge machine.

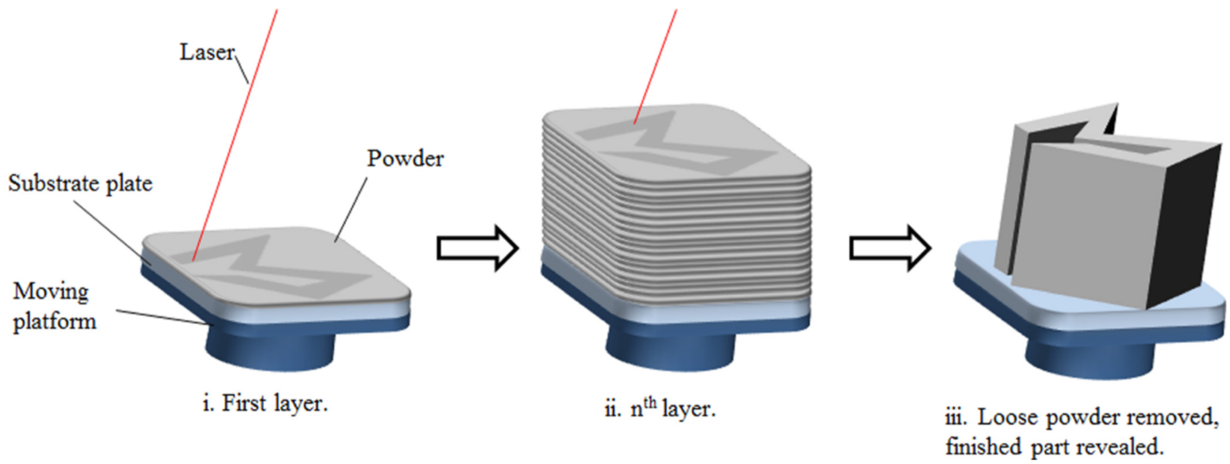

Fig. 2.7 Concept of SLM process [18]

Fig. 2.8 illustrates the overview of SLM process. The power source is a focused laser beam. Take the EOSINT M 270 system as an example. It utilizes a 0.2 kW Yb: YAG fiber laser with the san speed up to 7.0m/s. The building speed ranges from 2 to 20mm^3/s depending on the material.[19] The laser beam is scanned by a CAD program. The recoater arm acts as the powder distribution that drag the powder across build surface. The metal powder supply provides excess powders for dispensing. The X-Y scanning mirror is used as a beam deflective system, which makes the beam scan the corresponding part of each layer based on the CAD model. During the SLM process, the building chamber is filled with inert gas like nitrogen or argon to provide an atmosphere to protect the heated metal parts from oxidation. Some of the SLM machines can provide pre-heating to the substrate plate or the entire build chamber. The thickness of the layer usually ranges from 20 to 100 µm. The layer thickness was chosen to consider the balance of fine resolution and good powder flow ability. [20]

The parameters influencing the sintering processes include the laser type, frequency, hatch spacing, scanning speed, powder size and powder distribution. The absorptance of irradiation varies with powder materials, which influence the energy efficiency of the SLM process. A detailed discussion of the SLM parameters will be presented later.

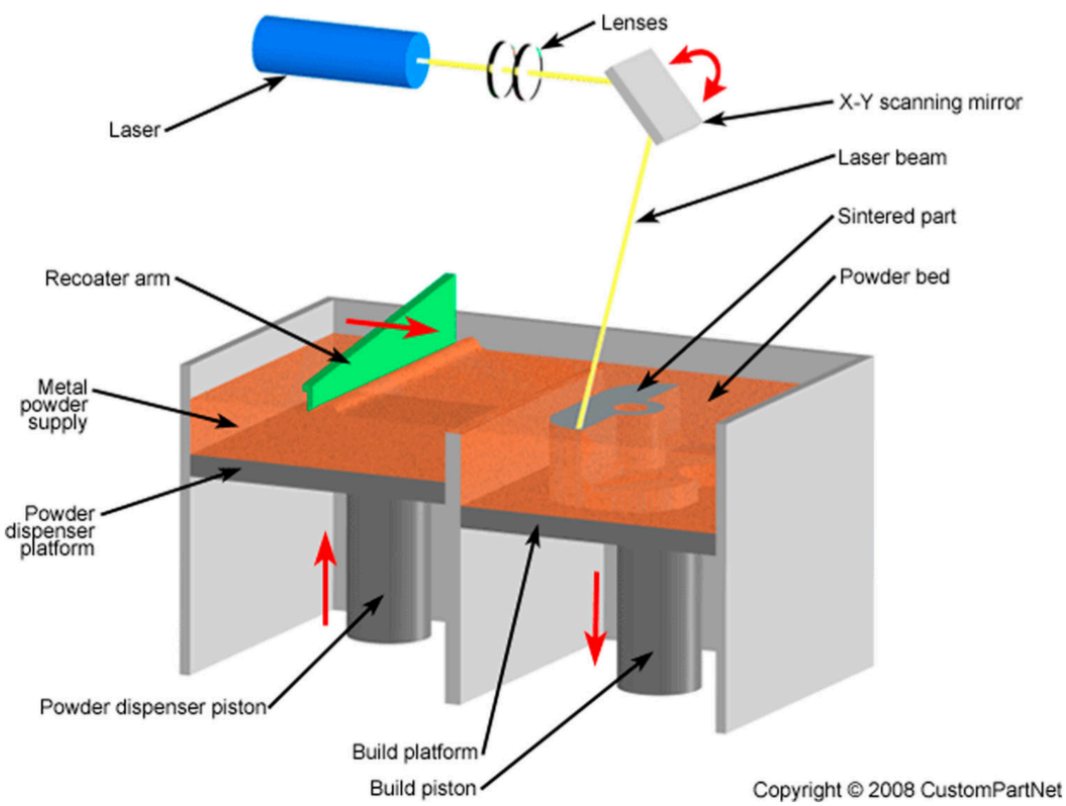

Fig. 2.8 A general illustration of SLM process

B. Selective Laser Sintering

SLS is a rapid prototyping process that allows to generate complex 3D parts by solidifying successive layers of powder materials on top of each other.[21] Fig. 2.9[22] provides an overview of the SLS process. A beam deflection system makes the beam scan each layer according to the corresponding cross section of the component as calculated from a CAD model. A powder deposition system is used for depositing the thin layers of powders, typically in the thickness of 0.1-0.3mm in the building container.[23]

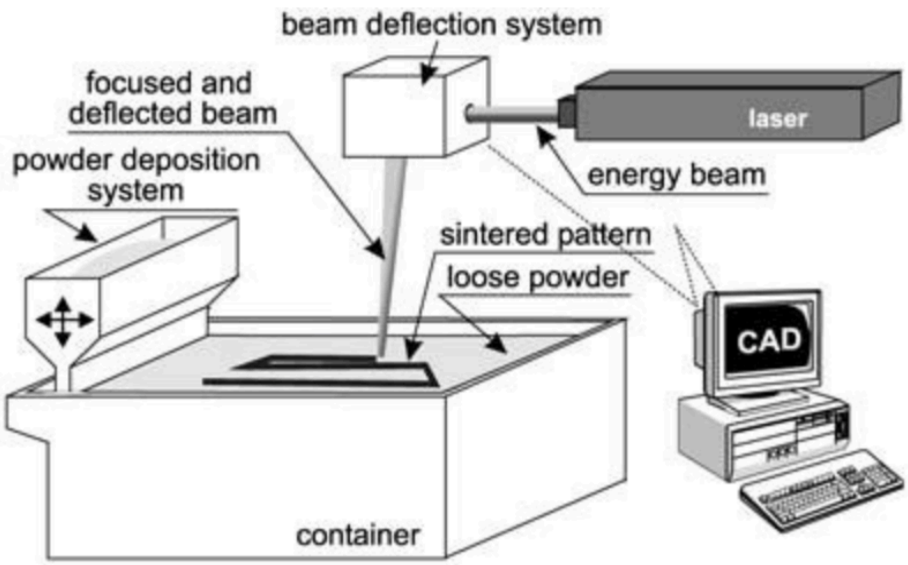

Fig. 2.9 A general illustration of SLS process [22]

SLS can be used to process any materials, not only metals, provided that the material is available in the form of powders and that powder particles tend to fuse when heat is provided. But for material powders displaying low fusion property, binder materials need to be added to the basis powder. The melting and evaporation of binders, resulting the fabricated parts with high porosity and low strength. Therefore, post-processing like heat treatment and material infiltration is needed to improve the components. That process is time consuming and added the cost.[18]

The melting processes melt the powders above the melting point and make the materials a homogeneous part. Sintering processes do not fully melt the powder, but heat it to the point that powder can fuse together in the molecular level. The controlled porosity could be achieved using SLS. So SLM leaves the fabricated component fewer or no voids. Compared with SLS, SLM is able to fully melt the metal powders, producing fully dense near net-shape components without the need of post processing. So SLM is superior AM method than SLS in product quality, processing time and binder free.

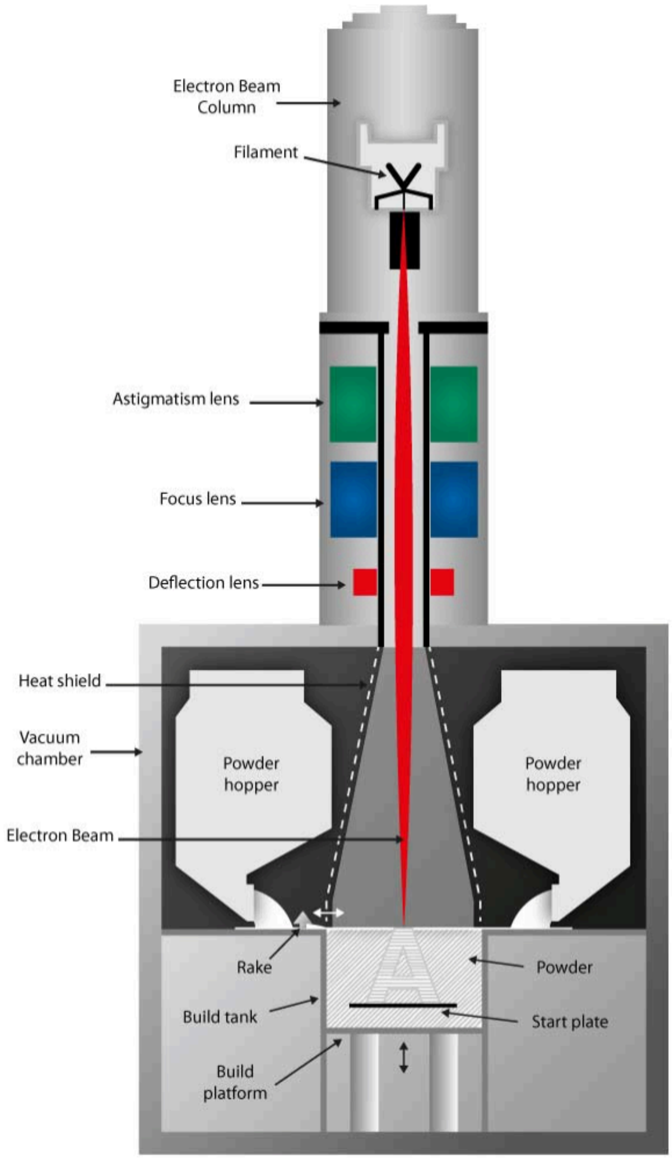

Fig 2.10[24] The schematic of EBM system. Image Courtesy of Arcam AB

C. Electron beam melting

Electron beam melting is a type of additive manufacturing for metal parts using an electron beam as the heat source. Electron beam system is illustrated in Fig. 2.10. Electrons are generated in a gun and accelerated with accelerating voltage. The hardware of EBM system is in fact a high-powered scanning electron microscopy (SEM), which requires electron source, magnetic coils to collimate and deflect the electron beam, and electron beam column.[17] The electrons are generated in the electron gun and accelerated with a voltage of 60 kV, focused using the a series of lenses and scanned by the embedded CAD program. The melt scan only melts selected areas as programmed by the CAD file. In terms of the powder feed, the powder hopper feed the powders due to the gravity and then the powders are raked by the metal rake to the building platform. The heat shield could protect the parts including powder hopper and metal powders from heating up. The vacuum chamber provides the inert atmosphere to protect the metal parts under high temperatures. The EBM system operates under a temperature of 10^{-4} Torr. The average powder sizes can range from 10 μm to 60 μm.[25]

D. Comparison of the laser and electron beam melting systems

Frazier et al., 2014[17] and Murr et al., 2012[25] presented the comparison of the two systems. The common aspect of those two processes are they all follow certain steps: machine set up, powder distribution, powder recovery and substrate removal. The principles of those two process all belong to AM process, which was fabricated layer by layer under the programming of CAD file. They differ in the hardware set up. The hard ware of SLM is consisted of a laser beam, leases and scanning mirror. In contrast, the EBM system is essentially a scanning electron microscopy. The powder distribution is also different. In SLM system, the soft distribution that drag the powder across the build surface like recoater arm is used. In EBM systems, the metal rake is used. The EBM system is operating under vacuum. The SLM is using either nitrogen or argon to prevent the components from oxidization. In addition, the atmosphere could provide sufficient heat conduction and component cooling. The building substrate is different. The building piston and building platform moves downward after one layer is printed during the SLM processes. While in EBM process, the powders surrounding the plate are sintered to provide stability, so the existing layers of the powder is not moved. The substrate also provides a path for heat dissipation. After the component is finished, excess powders need to be removed. As a result, the powders in SLM process is not being sintered as that in EBM, so they can be sifted directly after removing the sintered parts. For EBM, the powders are passed through a powder recovery system to recover and remove the sintered powders.

(ii) Direct energy deposition (DED)

Direct energy deposition includes all processes where focused energy generates a melt pool into which feedstock is deposited. It is a printing process commonly used for repairing or adding materials to existing components. The heat source could be a laser, electron beam, or plasma arc. The feedstock could either be powder (Fig 2.3) or wire (Fig. 2.6).

One of the most studies and commercialized DED system is using laser as heat source, powder-feed system. This was developed at Sandia National Laboratories and was presented as the Laser Engineered Net Shaping (LENS), as shown in Fig. 2.11. The DED machine consisted of a nozzle to deposit metal powders to deposition surface, which creates a converging powder stream. Then the laser beam is focused on the converging point to melt the targeted surface. Further material is added layer by layer. After solidifies, the new part is created or the existing parts are repaired. The deposits carried out in the atmosphere of argon. The motion control of the deposit could be from the CAD file or programmed manually.

This method has the ability to process more complex geometries due to the 3 or 5 axis systems flexible for the nozzle moves. Parts achieved with DED usually have a net shape geometry but with a rough finishing. Post-processing both thermally to relieve the internal stress and mechanically to get the desired resolution are needed.[27]

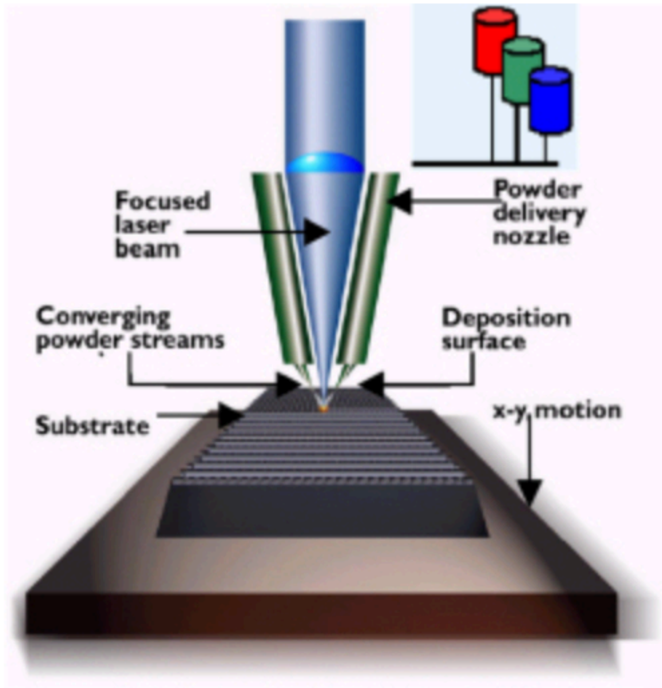

Fig. 2.11 Laser, powder-feed system (LENS). Courtesy of Welding Journal

(iii) Binder jetting

Binder jetting, a unique binder-based 3D printing technology that was developed at Massachusetts Institute of Technology in 1993. It was originally called Three Dimensionally Printing (3DP). Currently ExOne is the main manufacturer of binder jetting printers. The binder jetting process uses two materials, a binder and a base material powder. The binder is usually in the form of liquid. The process is similar to the process of SLS, but instead of using a laser to sinter materials, an ink-jet head deposits a liquid, which is a binder to binds the materials. Binder jetting is essentially a powder metallurgy process, so porosity is major problem. Sometimes infiltration is needed. Infiltrating a second metal, which is a lower melting temperature alloy to printed structure to achieve dense materials.

An illustration of binder jetting process is shown in Fig. 2.12. The binder jetting process begins with the powder feed supply being raised by a powder feed piston and a levelling roller distribute a layer of powder to the building chamber. Then liquid print head part deposits liquid binders to the targeted regions of the powder bed. One layer is formed through the bonding of binder and powders in selected region. The building platform is lowered by one layer through the movement of building piston. That process repeats to build layer by layer until the component is completely built. The loose powders can be brushed away and reused.

The bronze infiltration of porous iron produced by binder sintering process is most common used by the printers in ExOne.[17] When the binder together with the metal powder dries, a fragile binder-metal mix can be removed from the system and it takes 6 -12 hours to cure and gain mechanical strength. After curing, the component is heat treated at about 1100 °C for sintering. During the sintering process, the binders will burn off and the iron loose powders are sintered. When the partially sintered part is placed in contact with a molten pool of bronze to form a denser part, infiltration occurs. The final density of 95% is achieved. The second material need to have a lower melting temperature than that of sintered materials.

Consolidation is alternate to infiltration in producing the solid alloys. This process works by designing the distortion of the part geometry to accommodate uniform shrinkage during sintering. The part is sintered until the metal consolidates into the desired final part of geometry.[17] But how the distortion designed is not fully understood due to not much work has been done and publications on that aspect.

When printing, this process is generally faster than other methods. But the post processing process or curing add significant time to the whole process. It could be applied in almost any materials, not only metals. Due to the binders used, this process is not suitable for making components with high requirement of mechanical and structure.

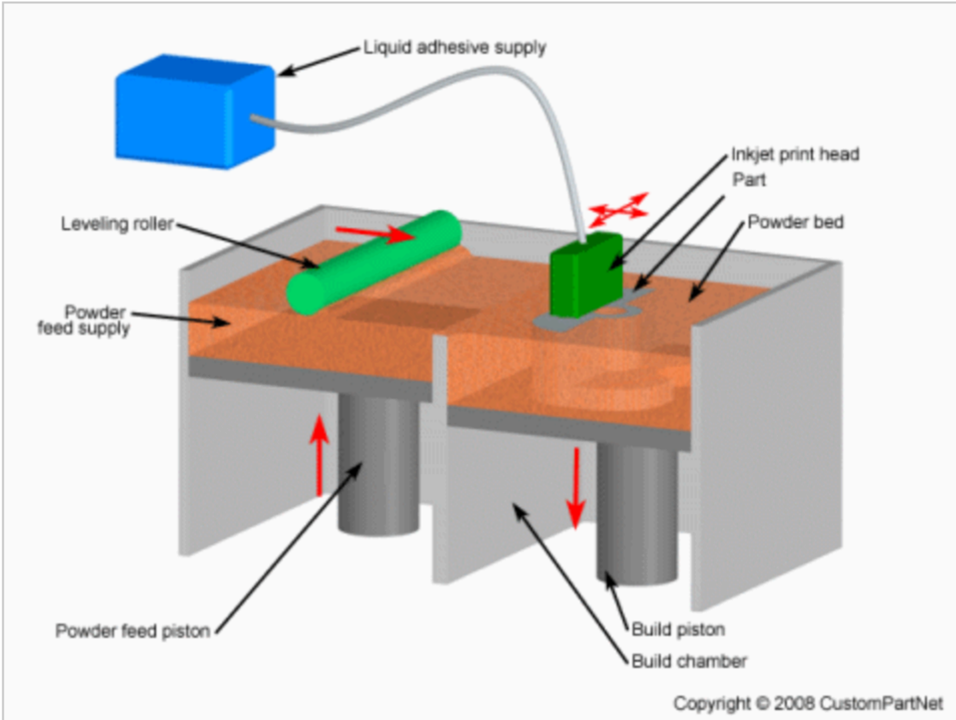

Fig. 2.12 The schematic of binder jetting process[28]

(iv) Sheet lamination

Sheet lamination processes includes ultrasonic additive manufacturing, which is used to process metals and laminated object manufacturing applicable for papers. UAM is a solid state additive manufacturing is a solid state additive manufacturing process that sequentially bonds metal foils together using ultrasonic metal welding, layer by layer, and integrates computer numerical control machining to remove materials to create the desired geometry during this additive build-up process.[29] UAM is a low temperature AM technique for metals. Instead of melting metal powers to form layers, metals are joined in the solid state through the disruption of surface oxide films using the ultrasonic vibrations under pressure. [30] Therefore, UAM is a hybrid of additive and subtractive manufacturing since this process incorporates layer manufacturing, welding and machining.

The general manufacturing process is illustrated in Fig. 2.13. The base plate is placed on the machine. Then metal foil is drawn under the sonotrode, which applies pressure through a normal force and the ultrasonic oscillations. So the metal foil is bonded to the plate. And under the force of ultrasonic oscillations, the following happens to metal foils: (1) it causes the oxides on metal surface to breakup (2) Localized asperities yield and collapse (3) Heat and pressure create high strength solid state bonding.

UAM has the abilities to join multiple metal types together thermally and mechanically. For temperature sensitive materials, the fabrication could undertook in a relatively low temperature, typically lower than the half of melting temperature of the metal matrix.[31] But post processing is typically require to achieve desired effect. The materials used are limited in the foil shape.

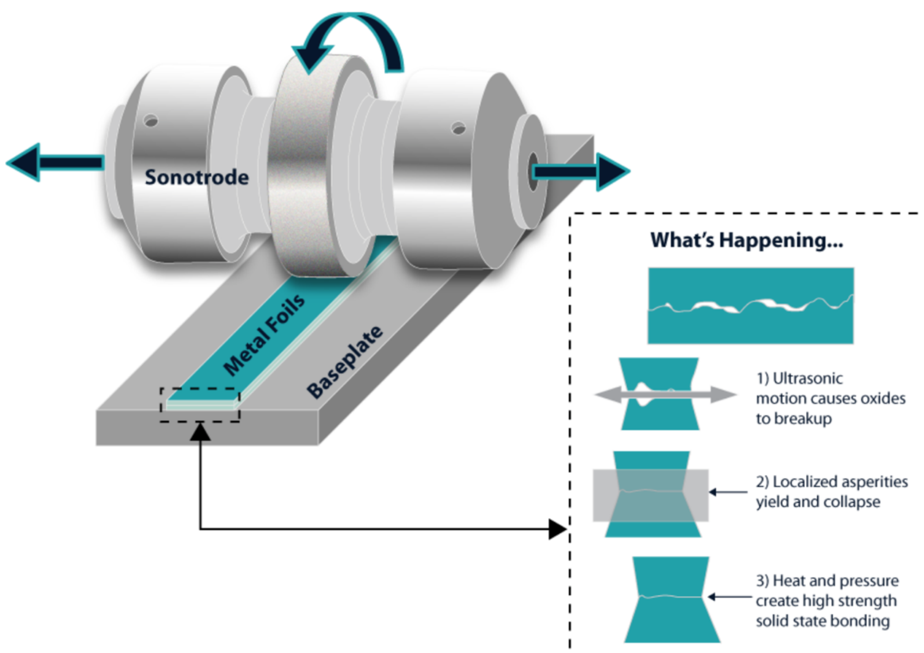

Fig. 2.13 A schematic of Ultrasonic Additive Manufacturing process

Chapter 3 The Processing Science of AM and the Influence on Material Properties

Despite the differences in the PBF and DED processes, there are common parts that occur in both processes. In this chapter, the physical phenomena and processing science of those processes will be explored. The processing parameters have a significant effect on the properties of materials. The processing parameters and their influence on the material property and defects formation will be discussed. The differences on the common part of the processing processes and the property fabricated components are compared.

In order to better understand the complex relationship between the processing sciences, defects, property of products of AM processes, a general process flow chart is helpful for analysis (Fig.3.1). The applications of AM products based on different metal systems will be covered in chapter 4.

As shown in Fig.3.1, the inputs are AM hardware & software, designed geometry, scan strategy, build chamber atmosphere and feedstock quality. The outputs are the mechanical properties of components, feature size & geometry scaling, the minimization of failed builds. In the flow chart, in between them is the physical phenomena that happen in that process, including the thermal interactions due to the beam interactions and heat transfer. (In order to have a better understanding of the processes, the physical phenomena will be talked first in this chapter, followed by the processing parameters and their influence on defects. 3.1 Physical Phenomena)

3.1 Beam-powder Interaction

The interaction of heat source and metal powders impacts the utilization of energy and could lead to the ejection of metal power and porosity. Sames et al. put forward four basis modes of particle ejection during beam melting processes: (1) Spatter injection (2) Electrostatic repulsion of powder particles in EBM (3) Kinetic recoil of powder in DED (4) Enhanced convection of powder in gas streams.[17]

In SLM, the powders are heated and melted by the laser beam and rapid solidification happens forming the desire component. The laser systems have progressed in the sequence of CO_2 laser ($\lambda \approx$ 10.6 μm) to Nd: YAG laser (($\lambda \approx$ 1.06 μm) and to is Yb: YAG laser. This is because metal powders have higher absorptance to the radiation of wavelength in the infrared region. In addition, the Yb: YAG crystal has a longer upper-state lifetime and a lower thermal loading per unit pump power.[18]

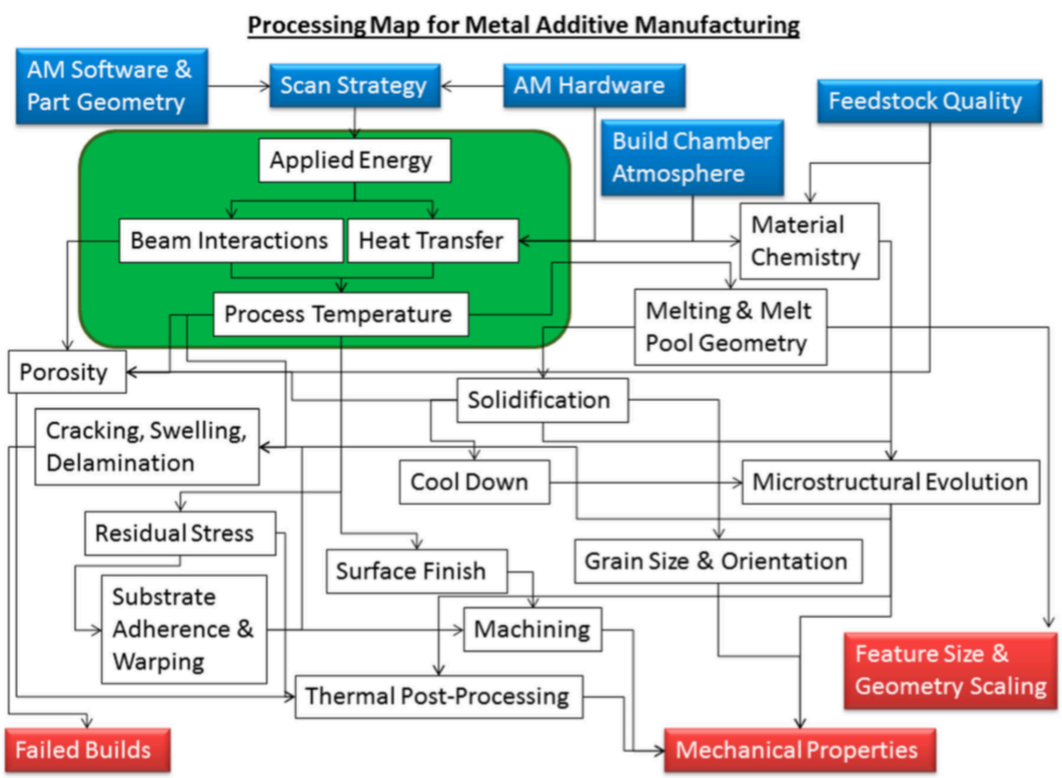

Fig. 3.1 Overview of relationship between processing parameters and the phenomena[17]

In SLM, the process parameters that are commonly adjusted for optimization are scanning speed, hatch spacing and layer thickness. An illustration of those parameters are shown in Fig. 3.2.

Improper combination of the parameters could lead to the defect formations. Insufficient energy, usually a combination of high scanning speed, low laser energy and large layer thickness, often result in balling due to lack of wetting of molten pool with the previous layer.[32] But high laser energy and low scanning speed may result in materials evaporation and keyhole effect.[33] Poor hatch spacing could result in the porosity in the fabricated parts.

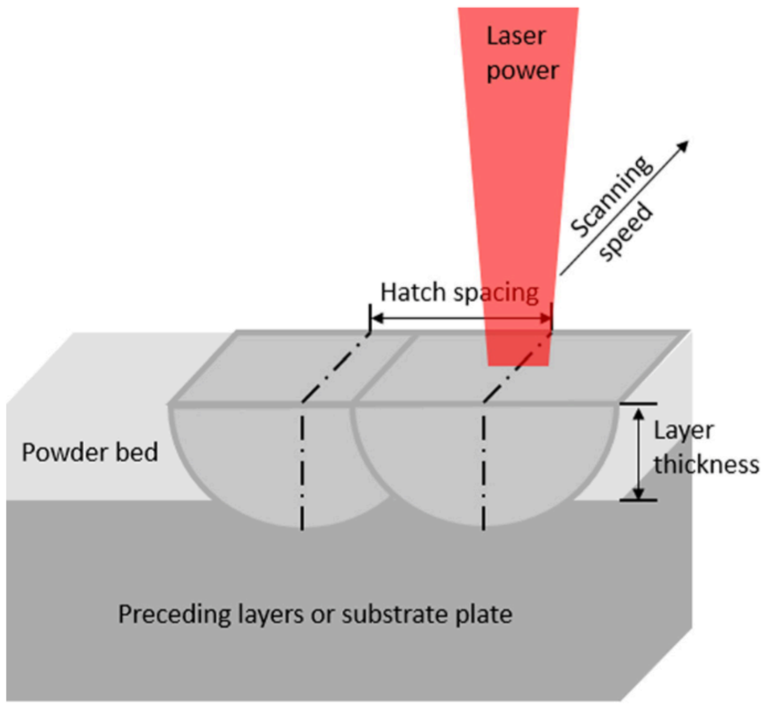

Fig.3.2 An illustration of the SLM process parameters[18]

The absorptivity of metal powders also need to be considered since laser imparts energy through photons. The absorptance of metal powders could be drastically different from that in the bulk state. Gusarov and Kruth built the isotropic specular reflection model and the diffuse reflection model to predict the absorptance of powder bed based on that of bulk materials, as shown in Fig. 3.4.[34] The models, substantiated by the experimental data, could be used to predict the absorptance of powders.

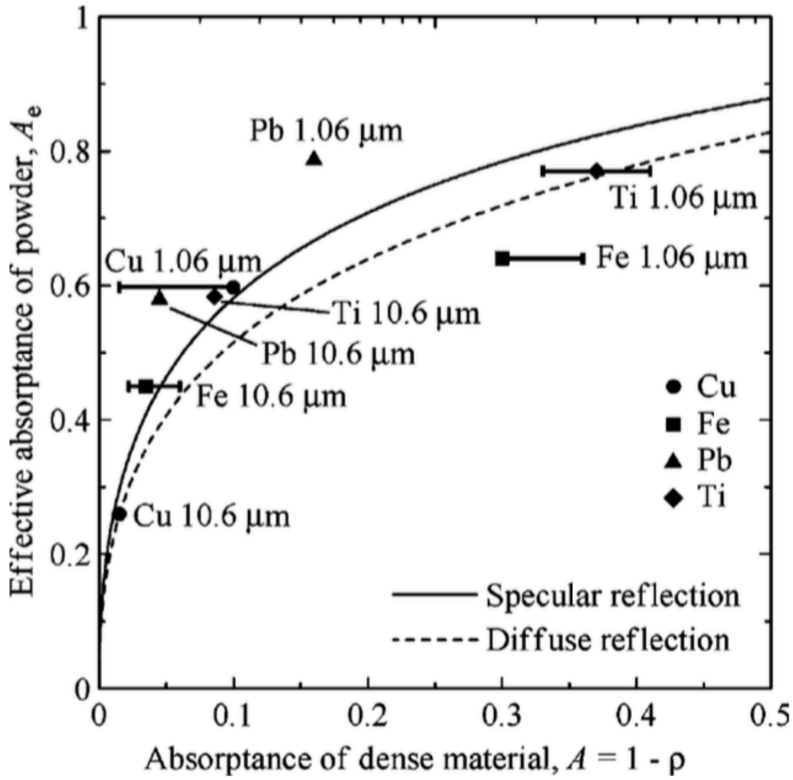

Fig. 3.4 Effective absorptance of powders A_e versus absorptance of dense materials A: solid line represents the isotropic specular reflection model; dotted line represents the diffuse reflection model; data points reflect experimental data. Image courtesy to 2005 Elsevier.

The energy distribution and the shape of laser powder has shown the potential to increase the energy efficiency. Loh et al. have conducted research on aluminum alloy 6061 to examine the different effects of Gaussian beam and uniform beam profile in SLM. Their research shows that a uniform beam laser could increase the productivity of SLM by reducing the hatch spacing.[35] Pulse shaping is a technique that used to distribute energy within a single laser pule and it provides an additional control over the heat delivered to the laser-materials interaction zone. Mumtaz et.al used a pulsed Nd: YAG laser to produce Inconel parts using pulse shapes that delivered different energy distributions. And the control of pulse shaping has shown the promise for increase the energy absorption and decrease spatter ejection.[36]

In the EBM process, the electrons are speed up to heat up the metal powders. The interaction between them not only transfer energy, but also electrical charge. If the electric repulsive force exceeds the force that hold powders with the substrate, the powders will be ejected from the powder bed, causing the phenomenon called 'smoking' (Fig. 3.5). [37] Electrostatic repulsion may lead to the formation of porosity. By using a rapidly scanned, diffuse beam to slightly sinter the melt surface before melting could reduce the electrostatic repulsion in EBM.[17] The bulk density and the electrical resistivity of the powder are important to the reduction of particles rejection in EBM system.[38]

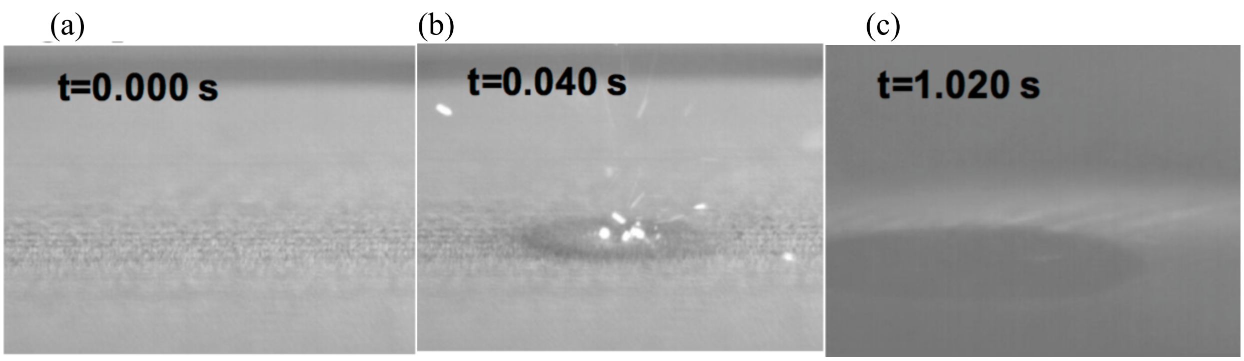

Fig 3.5. 'Smoking' caused by electrostatic repulsion (a) powder layer with approximate thickness of 0.1mm on substrate plate (b) powder layer at the time t=0.04s, particles interacting with the laser beam (c) particles are accelerated in vertical direction, at t=1.020s, the plates on longer covered with particles.[37]

During the powder-fed DED, due to the convection of powders in the fill or the shield of gas stream, some powders are sprayed into the melt pool and avoid deposition. Some particles may appear as dust in the inert gas atmosphere. If not recycled, this can be a waste of materials. Since those two way don't remove powders from the melt pool, so they are not the key factors influencing the formation of porosity. Therefore, during the process of beam-powder interaction, to control porosity should focus on the experimental control over sputter ejection and electrostatic repulsion.

3.2 Process Parameters

(i) Surface roughness and feature size of products

In additional manufacturing industry, surface roughness, geometrical accuracy and feature size of products are typical concerns for equipment operators. But they shouldn't be over-emphasized since post processing and machining usually takes place for the products. The minimum feature size is determined by the minimum size of the heat source and the size of feedstock. Table 1 summarized the data for PBF and DED processes.

Table 1 Typical layer thickness and minimum feature size or beam size for PBF and DED processes

Process	Typical layer thickness/μm	Minimum feature size or beam size
PBF-SLM[39]	10-50	75-100
PBF-EBM	50	100-200
DED-Powder fed	250	380
DED-Wire fed[40]	3000	16000

As can be seen from table 1, the resolution is high to low in the following sequence: SLM, EBM, powder fed-DED, wire-fed DED. The resolution of SLM, EBM also depend on the operating parameters. Due to the finer feedstock of powder fed than wire fed, powder fed DED has better resolution. Compared with PBF, DED is usually used to fabricate components with larger dimension and simpler geometry due to the relatively large feature size. There is a tradeoff between feature size and deposition rate. [17,25,41]

Surface roughness dependent on the orientation in the building process. The vertical surfaces of parts are rougher than the horizontal ones since 3D printing build components layer by layer.

(ii) Build chamber atmosphere

The atmosphere under which the parts were fabricated could influence the chemistry and heat transfer. As discussed in chapter 2, the SLM processes usually use inert gas like Argon or nitrogen filling the environment. The inert atmosphere could provide protection to the melt metal powders. The EBM processes happening in vacuum because of the accelerated electrons has high energy. To reduce the building up of charges in powder particles, a small quantity of helium is injected to the environment. The near vacuum environment result in the increase of melt vapourisation. DED processes are operated under the shield of gas flowing over the metal surface or under an inert gas atmosphere.

(iii) Feedstock quality

The quality of feedstock in the AM processes has an important impact on the final products. The quality of the powders is determined by the shape, size, morphology, composition and internal porosity. And it affects physical properties such as followability, apparent density.

The techniques used to produce powders impacts the qualities directly. The techniques include gas atomization, rotary atomization, plasma atomization, plasma rotating electrode process. Among them, plasma atomization and plasma rotating electrode process could produce powers in highly spherical shape and with smooth surfaces. Rotary atomization yields powders with irregular shape. Gas atomization tend to produce powers with a large amount of satellite. In addition, during gas atomization, the inert gas could be trapped into the powders and cause porosity. [17,42]

The recycled powders need to take chemical composition measurement due to the evaporation loss, reaction with oxygen, nitrogen or other gases and contamination during the production process. Tang et al. have researched on the effect of powder reuse times on the AM of Ti-6Al-4V by EBM and found that oxygen content increased from 0.08 to 0.19% by weight, while aluminum content decreased from 6.47 to 6.37% and vanadium content decreased from 4·08 to 4·03% over 0 to 21 reuse cycles.[43]

3.3 Defects in Metal AM parts

The common defects that could be found in metal AM parts are porosity, balling, cracking, delamination, swelling and residual stress. These defects can be caused due to improper way of manufacture, improper processing parameters or the defects existing in powders prior to fabrication.

Porosity can be powder induced, process induced or happens during solidification. The pores formed are different and are differentiated in Fig. 3.6[43] Based on the studies, porosity formation is mostly caused by processing, so the process parameters need to be properly set up to avoid creating pores.

Process-induced porosity refers to the pores formed by processing technique, formed when applied energy is not enough for sufficient melting metal powders or the applied energy is too high and result in spatter rejection. When not enough applied energy focused on the powders, lack of fusion occurs. When the applied energy is too high, spatter ejection may occur, which is known as keyhole effect.

Balling forms due to insufficient wetting of the preceding layer and surface tension where molten metal forms spheroidal beads.[44] It obstructs the continuous melt lines, forming rough and bead-shaped surfaces. More intense extent of balling can aggravate in subsequent layers and the layers are overcrowded with large metallic beads that extend above the powder bed.[32] Different extent of balling is shown in Fig. 3.7.

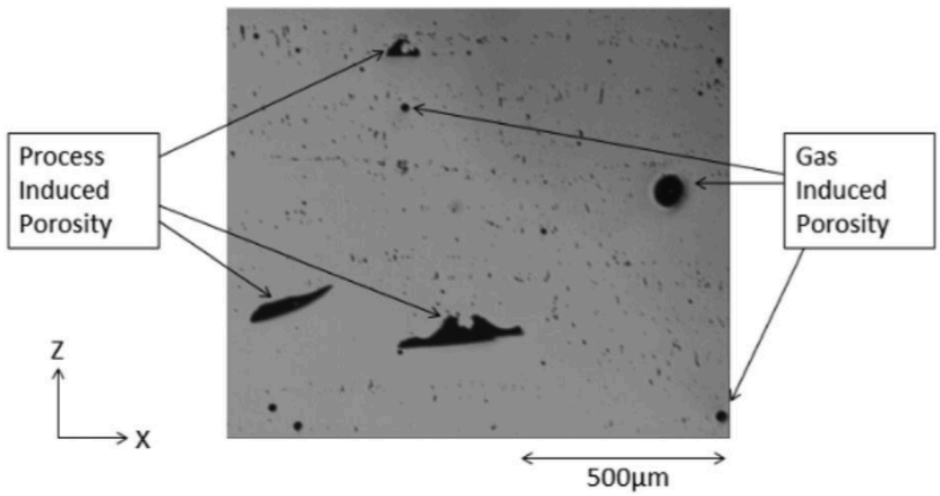

Fig. 3.6 Light optical microscopy showing the comparison of process-induced porosity to gas induced porosity[43]

Li et al. ‘s research on balling process has shown that balling could be greatly reduced by keeping the oxygen level at 0.1%, applying a combination of high laser power and low scanning speed or applying laser re-scanning.[45] Das et al. illustrated that the oxide film on the preceding layers will impede the interlayer bonding and wetting of powders. [44]Poor layer bonding could easily lead to the delamination of parts. Therefore, lowering the oxygen layers to prevent of oxide film formation and use laser scanning repeatedly to break to oxide films and wetting the powders are key to reducing balling phenomena.

Cracking may occur during solidification or heating process. Porosity may lead the microstructure cracking. Delamination is the separation of adjacent layers within parts due to incomplete melting between layers. Fig. 3.8 shows the delamination lead to the cracking between layers. When the processing temperature is too high, the surface tension together with the melt pool size may lead to swelling.[17]

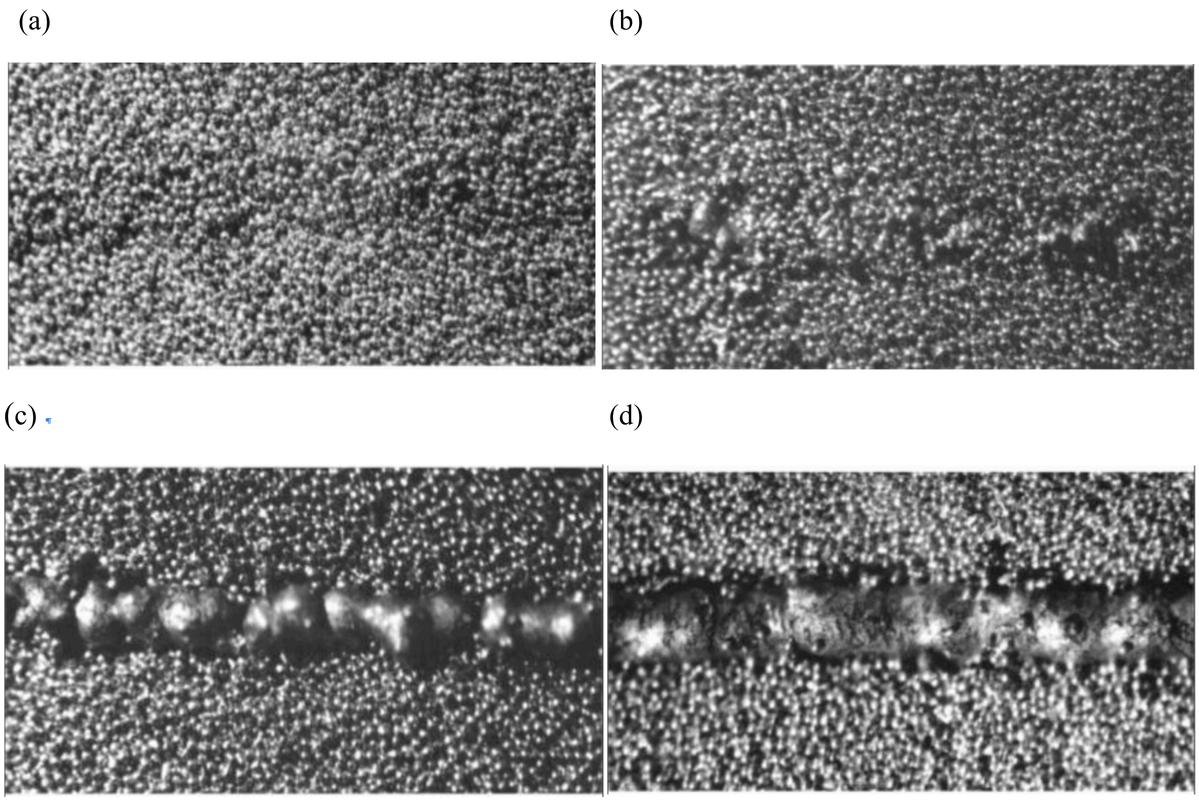

Fig. 3.7 Illustrations of single-layer formed due to selective laser melting of powder under adjustable balling processes: (a) ordinary sintering before the balling processes start; (b) beginning of the balling process; (c) strongly limited balling process; (d) light limited balling process.[45]

Regarding the crack formation in AM parts, there are different material-dependent mechanisms.[46] Here two types of mechanism are discussed. For some materials, solidification cracking can occur if the applied energy is too high and stresses are induced between the solidified areas and not yet solidified areas in the melting pool. So it depends on the solidify nature of materials and caused by the strain on the melting pool. Upon the higher energy that energy source provided, the thermal strain is larger. So for solidification cracking, adjust the applied energy properly could reduce the cracking. Grain boundary cracking occurs along the grain boundaries.

The cracking is dependent on the materials in grain boundary morphology and the formation or dissolution of precipitates.[46]

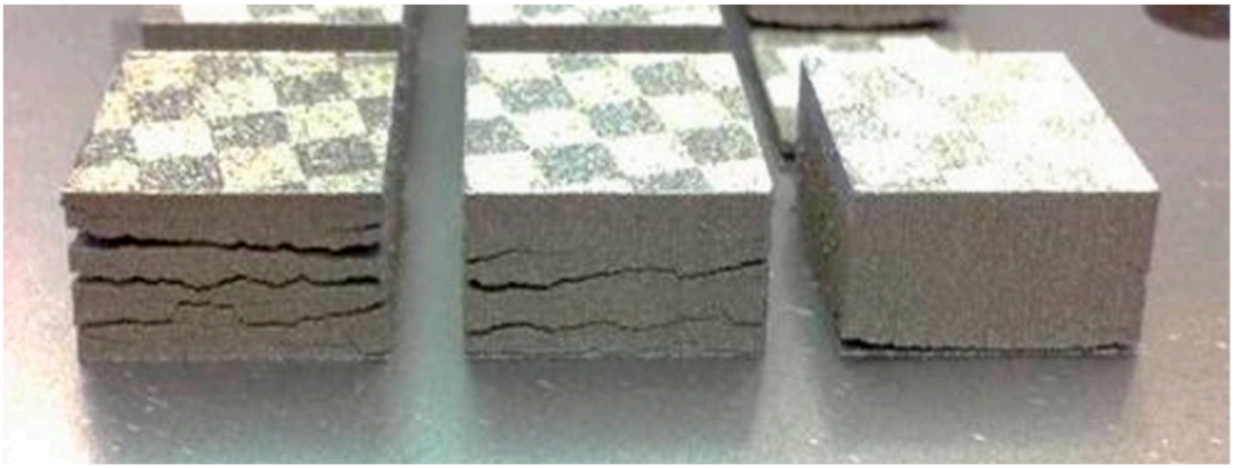

Fig. 3.8 M2 parts produced by SLM[47]

Solidification cracking and grain boundary cracking are both phenomena that occur within the microstructure. However, generally cracking is sometimes used to describe macroscopic cracks in the material. These cracks may nucleate due to other macroscopic defects such as delamination that are not related to excessive energy input.[47]

Residual stress is a commonly seen defect in AM products and it has a negative effect on the mechanical properties of AM parts. Residual stress can occur through a variety of mechanisms including plastic deformation, temperature gradients and phase transformations. In AM processes, the main concern is the large thermal gradients. Residual stress is defined as a stress remains in a material after the original cause of the stresses has been removed. If residual stress exceeds the local yield stress of material, warping or plastic deformation may occur. If residual stress exceeds the local ultimate tensile strength of the material, cracking or other defects may occur. Macroscopic residual stresses have larger effect on the whole component compared with the microscopic ones. While microscopic residual stresses resulting from precipitates or atomic dislocations are more localized. Macroscopic residual stress can be thermally introduced in metal AM by rapid and uneven cooling or heating during and after solidification.[17,48]

The residual stress can be measured using the techniques such as micro-hardness, x-ray diffraction, neutron diffraction.[48,49] Rangaswamy et al. has demonstrated that residual stress is closely related to temperature. It tends to be higher for substrates operating near room temperature as in DED or SLM than those operating at higher temperature such as EBM.[50] Heating of the substrate could reduce the residual stress.[48] Therefore, the fabricated parts by EBM process have a lower residual stress than those by SLM and DED processed due to the higher operating temperature.

Chapter 4 Metals and Application

Currently the metal materials used in additive manufacturing include steels and iron-based alloys, pure titanium and titanium alloys, nickel-based alloys, cobalt-chromium alloys, gold and silver. As the new techniques and applications emerge, the range of metals available for use in AM continues to grow.

AM materials have high potential for a wide range of applications in the areas of aerospace, energy, biomedical, semiconductor manufacturing and customer products. To utilize the full potential and market of AM, the materials used will need further research and development. Despite the progress and improvement on the new AM materials and processing techniques, there are remaining challenges, which will be discussed in this chapter. The commonly used metal systems, their properties and applications are explored.

As previously mentioned, the publications for AM metals processing technique mainly focused on PBF and DED. In this chapter, the components are manufactured through SLM processes.

4.1 Steel and Iron-based Alloys

Based on the publications, M2 tool steel and 316 stainless steel are intensively studied. Jandin et al. reported the fabrication of 316L stainless steel powder by SLM for the first time. In their study, the 316L stainless steel powders were processed using yetterbium fiber laser with a wavelength of 1065 nm.[51] In 2010, Tolosa et al. achieved 99.9% relative density with of 316L stainless steel powder.[52] Yap et al. presented an excellent review of SLM materials, with the comprehensive data and substantive research reviews on the properties of different metal systems.

Different types and steels and iron-based alloys are investigated, including H20 tool steel, 17-4 precipitation hardening steel, Fe-Ni, Fe-Al, Fe-Cr-Al alloys, are also been tested despite there is not as much publications as that on steel. So far, the research works mainly investigated the optimization of processing parameters to achieve full density parts.[18]

(i) Property

A. Relative density. Relative density is one important quality indicator. Relative density is the ration of density of the AM product to the theoretical density of the bulk materials. The theoretical density could be calculated based on the ideal crystal structure and atomic weight. ASM International also provides the material data sheet for reference. Most SLM steel and iron-based alloys could achieve the relative density above 90%. Table 2 summarizes the reported maximum relative density of various SLM materials.

Table 2 The reported highest relative density of SLM steel and iron-based alloys[18]

Material	Highest relative density, %
Fe	99.00
Fe + 0.8% C	93.00
Fe-Al intermetallics	98.00
Fe_3Al	99.50
Fe-Ni	98.00
Fe-Ni-Cr	99.50
Fe-Ni-Cu-P	97.50
304L stainless steel	92.00
316L stainless steel	99.90
316L stainless steel	99.95 (laser remelting)
H13 tool steel	90.00
H20 tool steel	99.50
M2 high speed steel	97.00
AISI Marage 300 steel	99.99
Ultra high carbon steel	92.00

B. Strength. Steel has superior strength so it is important for its application. SLM parts usually have better strength than cast since the chemical composition is more uniformly distributed. Table 3 shows the highest yield strength and ultimate tensile strength of SLM steel and iron-based alloys.

Table 3 Highest reported tensile strength of SLM steel and iron-based alloys[18]

Material	UTS (MPa)	YS (MPa)	Elongation (%)
Fe	411.5	305.3	…
Fe-Ni	600	…	…
Fe-Ni-Cr	1100	…	…
Fe-Ni-Cu-P	505	425	…
15-5 PH steel	1450	1297	12.53
15-5 PH steel	1470	1100	15.00
304 stainless steel	717	570	42.80
316L stainless steel	760	650	30.00
Maraging steel	1290	1214	13.30

C. Surface roughness. For SLM process, post processing is need to reduce the surface roughness of component. And in general, for AM processed, machining is needed. It also depends on the resolution requirement of the products. As shown in Table 4, the surface roughness could be as low as 3.78 µm. The surface roughness commonly seen in the SLM products are about 20 µm.

Table 4 Lowest reported surface roughness of SLM steel and iron-based alloys[18]

Material	Surface roughness, R_a (μm)
Fe-Ni	10
Fe-Ni-Cr	10
304L stainless steel	25.7
316L stainless steel	5.82
316L stainless steel	5.00 (sand blasting)
316L stainless steel	2.00 (laser re-melting)
H20 tool steel	3.78 (shot-peening)
Ultra high carbon steel	18.0

D. Micro-hardness. There are many techniques and units set for the micro-hardness. The highest reported micro-hardness of SLM steel and iron-based alloys is shown in Table 5.

Table 5 The highest reported micro-hardness of SLM steel and iron-based alloys[18]

Material	Micro-hardness (HV)
Fe-Al intermetallic	800
Fe_3Al	353
Fe-Ni	232 (from 220 HB)
Fe-Ni-Cr	450
Fe-Ni-Cu-P	230
304L stainless steel	217
316L stainless steel	279
316L stainless steel	272 (from 104 HRB)
H20 tool steel	336 (from 34 HRC)
M2 high speed steel	900
Maraging steel	412 (from 42 HRC)
X110CrMoVAl 8-2 tool steel	493
Ultra high carbon steel	475

(ii) Application

The parts manufactured through SLM methods are still more expensive than that of conventional manufacturing, so they are used in high-end areas such as medical applications. The advantage of produce metal parts with complex geometries allow the fabrication of parts with inner channels, which meet the requirement of heat exchangers and light weight structures. And they could be applied in aerospace and automotive industries. The applications depend on their mechanical properties, biocompatibility.

The benefit of SLM parts in medical applications lies in easily customized. The ability to create complex structures make the fabrication of light-weight structures. There are published research in this area. Kruth et al. published the biocompatible metal frames could be used as dental prostheses.[53] Wang et al. optimized SLM parameters and lead to high shape precision of customized brackets with the application in orthodontic products.[54] 316L stainless steel was mostly often used in the research of light structure materials. Shen et al. studied the mechanical properties and the failure mechanism of the sandwich structure.[55] Due to the high hardness of the SLM of steel or iron based alloys, the products can be used in tooling.

4.2 Titanium and Titanium alloys

The published research of titanium and its alloys is second to that of steel and iron-based alloys. Pure titanium and Ti-6Al-4V are intensively studied. Due to the active chemical nature of titanium in the liquid state, producing in AM methods which under inert gas or near-vacuum environment could protect the components. Besides, titanium and its alloys has excellent strength to weight ratio, making them suitable materials for aerospace products. The biocompatibility that titanium possess enables their application in medical applications.

(i) Properties

A. Relative density. Compared with steel and iron-based alloys, the relative density of titanium and its alloys is higher. And the highest reported data on Table 6 has shown the parts almost achieve the theoretical density. That means only a limited small portion of porosity exist in the parts and the mechanical properties are enhanced.

B. Strength. Titanium parts through SLM can achieve better strength than that of casting due to the more uniform chemical composition and microstructure. The highest reported strengths of titanium parts are shown in Table 7.

C. Surface roughness. There is few reports on the surface roughness of Ti parts. Zhang et al. reported the surface roughness of pure Ti is 5 μm.[56]

Table 6 Highest reported relative density of Ti and Ti alloys

Material	Highest relative density, %
cpTi	99.50
cpTi	99.90 (under vacuum)
Ti-6Al-4V	99.98
Ti-6Al-7Nb	99.95
Ti-24Nb-4Zr-8Sn	99.50

Table 7 Highest reported strength of Ti parts

Material	UTS (MPa)	YS (MPa)	Elongation (%)
cpTi	654	522	17.0
Ti-6Al-4V	1250	1125	6.00
Ti-6Al-7Nb	1515	1440	1.40
Ti-24Nb-4Zr-8Sn	665	563	13.8

D. Micro-hardness. The highest reported micro-hardness of Ti parts is shown in Table 8.

Table 8 The highest reported micro-hardness of Ti parts

Material	Micro-hardness (HV)
cpTi	308
Ti-6Al-4V	613
Ti-6Al-7Nb	464
Ti-24Nb-4Zr-8Sn	225

(ii) Applications

Titanium has great potential on biomedical applications due to the biocompatibility and its high specific strength and elastic moduli close to that of human bones. Thus, the titanium body implants are a focus of the research. Santos et al. built the bones and dental crowns using pure tiannium.[57] Warnke et al. researched on tissue engineering and porous titanium alloys scaffolds and has shown SLM Ti64 scaffold allows the growth of bone cells.

The fabrication of titanium scaffolds could also be applied in aerospace area, enabling the fabrication of light weight structure parts. There has been multiple research and publications on porous titanium parts. Wang et al. researched on the porous TiH_2-Ti scaffolds with a high porosity of about 70%.

4.3 Nickel-based Alloys

Nickel-based alloys are one of the most intensively studied by researchers followed iron-based alloys and titanium alloys. Inconel, the Cr-Ni-Fe alloy are the main focus due to the resistance to high temperature. NiTi, is a type of temperature-sensitive shape memory alloy.

(i) Properties

A. Relative density. The highest reported relative densities of Nickel-based alloys are shown in Table 9. As it shown that Inconel 625, Inconel 718, Niomonic 263 achieved near 100% relative density.

Table 9 Highest reported relative densities of Nickel-based alloys

Material	Highest relative density, %
Inconel 625	95.00
Inconel 718	99.98
Chomel	88.00
Hastelloy X	99.75
Nimonic 263	99.70

B. Strength. The strength of SLM Nickel-based alloys has a higher strength that the casting counterparts. The reason is same to that of titanium parts and iron parts. The highest reported strength of Nickel-based alloys is shown in Table 10.

Table 10 Highest reported strength of Nickel-based alloys

Material	UTS (MPa)	YS (MPa)	Elongation (%)
Inconel 625	1030	800	10.0
Inconel 718	1148	907	25.9
IN738LC	1184	933	8.40
Hastelloy X	930.5	814	35.0
Nimonic 263	1085	818	24.0

C. Surface roughness. There is hardly any report on the surface roughness of Nickel-based alloys. As the AM technology develops and more applications of AM Nickel alloys, there should be more research on the surface roughness of Nickel alloys.

D. Micro-hardness. There are not many tests on the micro-hardness. But research found that aging treatment could improve the micro-hardness of Nickel-based alloys. It could be seen from Table 11.[18]

Table 11 Highest reported micro-hardness of Inconel and Nickel-based alloys

Material	Micro-hardness (HV)
Inconel 625	163 (from HRA)
Inconel 718	365
Inconel 718	470 (after aging treatment)
Chomel	740
Nimonic 263	370

Chapter 5 Summary and Future Research Trends

In this thesis, an overview of the basics of the additive manufacturing is covered. A fundamental understanding of the advantages of 3D printing, the historical development, how the AM products are produced has been shown. Among a variety of category of materials, metals stood out due to their potential application in aerospace, medical, energy and the benefits of able to customization, reduce materials waste and cost, and fabricate complex geometry.

A diverse set of processes have been used to fabricate 3D objects. The AM manufacturing systems can be divided into powder bed, powder fed, wire fed depending on the feedstock. The way how the feedstock works, the strength and weakness of the system corresponding upon the requirement of the components are explored. Based on the standards on process terminology set by ASTM, each AM technique that could process metals are categorized. The working principals, process parameters, examples of machines and machine manufactures, their advantages and weakness of those methods are compared and discussed.

The defects of AM components are essential to determine the quality of AM manufacturing. Process parameters plays a key role in decreasing or even eliminating the AM defects. Therefore, the interactive relationship between materials, processing, property and applications are explored. Some physical phenomena and some commonly adjusted parameters for optimization are explained. The defects that commonly exist in AM products and how to avoid or alleviate through parameters adjustment and materials preparation are illustrated.

The most studies AM metals and alloys are steel and iron-based alloys, titanium and titanium-based alloys, Inconel and nickel-based alloys. The relevant noted research, their properties and applications are reviewed.

However, to utilize the full potential of AM, every part of AM process including design, process control, supply chain, powder properties and standardization need to be further developed. Based on the roadmap for additive manufacturing and measurement science roadmap for metal-based additive manufacturing, the desired capabilities and recommendations for future research is summarized below:[6,11]

Design

- Create conceptual design methods to aid designers in defining and exploring design space enabled by AM.
- Produce a new foundation for computer-aided design systems to overcome the limitations of existing solid modelling in representing complex geometries and multiple materials.
- Provide a multiscale modelling and inverse design methodology to assist in navigating complex process-structure-property relationships.
- Create methods to model and design with variability: shape, properties, process, etc.

Process Modeling and Control

- Develop predictive process-structure-property relationships integrated with Computer Aided Design/Engineering/Manufacturing tools
- Create closed-loop and adaptive control systems with feedforward and feedback capabilities.
- Produce new sensors that can operate in build chamber environments and sensor fusion methods.

Materials, Processes and Machines

- Develop a better understanding of the basic physics of AM processes to capture the complexity in the multiple interacting physical phenomena.
- Create scalable, fast material processing methods using line or area processing to greatly increase machine throughput.
- Produce open-architecture controllers and reconfigurable machine modules.
- Exploit Unique AM characteristics to produce epitaxial metallic structures, fabricate functionally gradient materials and multiple materials, and embed functional components during fabrication processes.
- Screen methodologies to answer the question as to why some materials are processable by AM and some are not; and tools for AM fabrication of structure and devices atom by atom and design for nanomanufacuting.
- Develop and identify sustainable materials including recyclable, reusable, and biodegradable materials.

Supply chain capabilities

- Reliable, available and consistent powders for AM
- Ability to create feedstock for AM from ore elements
- Greater availability of materials
- Ability for recycling and reuse of AM materials

Metallurgical/powder properties knowledge

- Quantification of defect types, frequency, size and impact on properties
- Established surface characteristics and effects on fatigue properties
- Better understanding and characterization of AM materials and input materials, including powder size, shape and chemistry

Standard specification database

- Strong database of materials properties
- Public access to common alloy specifications for AM processes
- Machine-independent material properties for deposited metals
- Micro-structural database with images at each step, including feedstock, both virgin and recycled; in-situ process and finished build.

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