Consolidation Behavior of Metal Powder in Additive Manufacturing

Submitted in accordance with the requirements for the degree of

Doctor of Philosophy in Engineering

By

Mohd Rizal Bin Alkahari

ABSTRACT

Additive manufacturing (AM) is a relatively new and emerging manufacturing technology that is able to revolutionize the manufacturing industry. This is due to its high flexibility in processing different types of material under various conditions. However, capability of a product to have desirable quality comparable to traditional processing techniques is still not achievable. Consolidation behavior and influences of processing parameters are important in determining the part quality. Therefore, in this research, consolidation behavior of metal powder was examined by monitoring the real time consolidation process and surface temperature. A high-speed camera was utilized with telescopic lenses in order to monitor interaction of laser and material within the fusion zone (FZ). In order to investigate the consolidation temperature, a two-color pyrometer was used. The influences of processing parameters were examined. It was found the temperature and consolidation behavior were affected by the processing parameters. The line consolidation characteristics were analyzed according to the line consolidation width, FZ, melt pool and splattering behavior. Based on the study, the line consolidation can be classified into five different consolidation types. These types are continuous, discontinuous, ball shaped, weak and very little consolidation. The consolidation mechanisms that occurred during line and area consolidation were also reported. Other than that, the properties of the consolidated material were studied, and its potential for the development of a permeable structure was investigated. It was found that the properties of the structures developed via AM relatively good and feasible to be used for the manufacturing of injection mold

TABLE OF CONTENT

NOMENCLATURE

K	Thermal conductivity	W/(m·K)
K_{powder}	Thermal conductivity of metal powder	W/(m·K)
z	Distance to thermocouple junction	mm
ρ_{powder}	Bulk density of metal powder	kg/m^3
C_p	Specific heat of metal powder	J/(g·K)
T_{max}	Measured time to maximum voltage point	s
Δt	Irradiation time	s
t_{cp}	Heat transfer time from heat source	s
a	Heat source radius	mm
t	Time	s
$K_{consolidated}$	Thermal conductivity of consolidated material	W/(m·K)
$\rho_{consolidated}$	Density of consolidated material	kg/m^3
C_c	Specific heat of consolidated material	J/(g·K)
α	Thermal diffusivity of consolidated specimen	m^2/s
$t_{0.5}$	Time of heat pulse reaches to ½ of max temperature	s
$L_{consolidated}$	Thickness of consolidated material	mm
K_{solid}	Thermal conductivity of solid material	W/(m·K)
D	Average particle diameter	µm
A_r	Absorption ratio	%
t	Layer thickness	µm

P	Laser power	W
V	Scan speed	mm/s
H	Hatching size	mm
E	Energy density	J/mm^2
d	Spot size diameter	mm
$\O$	Porosity	%
λ	Wavelength	mm
J	Scan length	mm
f	Shutter speed	fps
d_c	Core diameter	µm
ξ_m	Acceptance angle	°
$e(\lambda, T)$	Emissivity of the object	
w	Constant	
$F(\lambda)$	Spectral transmittance of optical fiber	
$L(\lambda)$	Spectral transmittance of condenser	
$D(\lambda)$	Spectral transmittance of detector cell	
$G(\lambda)$	Spectral transmittance of filter	
T_{Line}	Temperature during line consolidation	°C
T_{Area}	Temperature during area consolidation	°C

CHAPTER 1 : INTRODUCTION

1.1 BACKGROUND

Additive manufacturing (AM) is a relatively new and emerging manufacturing technology that may revolutionize the manufacturing industry. The initial development of the technology dates back approximately 30 years with the introduction by Kodama of a new method for manufacturing three-dimensional models [1]. This was followed by the first commercialized streolithography-based AM, produced by 3D Systems [2]. Various types of materials are used in AM including metallic materials [3]. Therefore, it has been speculated that AM is the third industrial revolution after mechanization in the 18th century and the introduction of the assembly line in the 20th century [4].

The growth of the global market for the AM industry is indicated in Fig. 1.1. The growth was surveyed by Wohler Associates Inc., a leading consultancy on AM. It reported on the growth of the AM industry from 1988 to 2012 and revealed there to have been a high level of growth with only a slight decrease in 2009 [5]. They also showed a significant increase in the revenue of AM, which indicates a relatively strong demand for AM. In addition, it is reported that the metal-based AM system has been gaining in popularity in the industry in recent years.

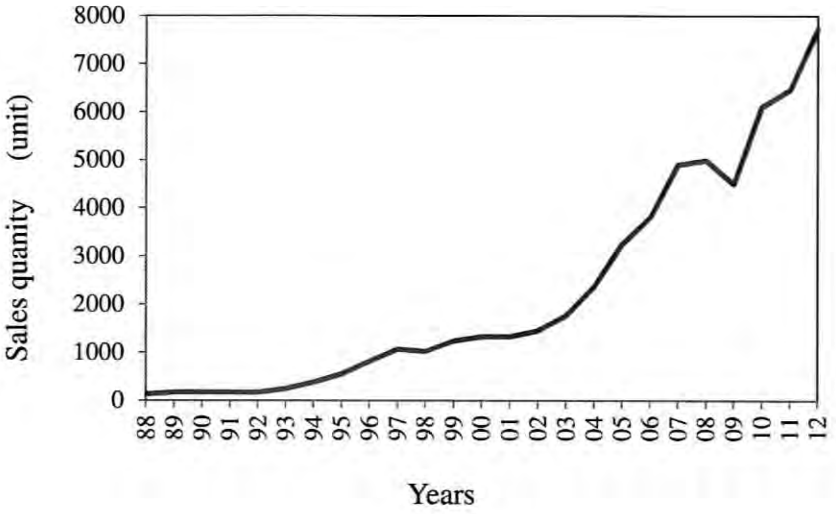


Fig. 1.1 Growth in the additive manufacturing industry [5]

With the realization of the potential of AM in generating revenue and its economic impact, the installation of AM systems is increasing worldwide. The installation of AM systems is presented in the pie chart in Fig. 1.2. The percentage of AM use by the country shows that the US (38%), Japan (9.7%) and Germany (9.4%) have the highest number of AM systems installed.

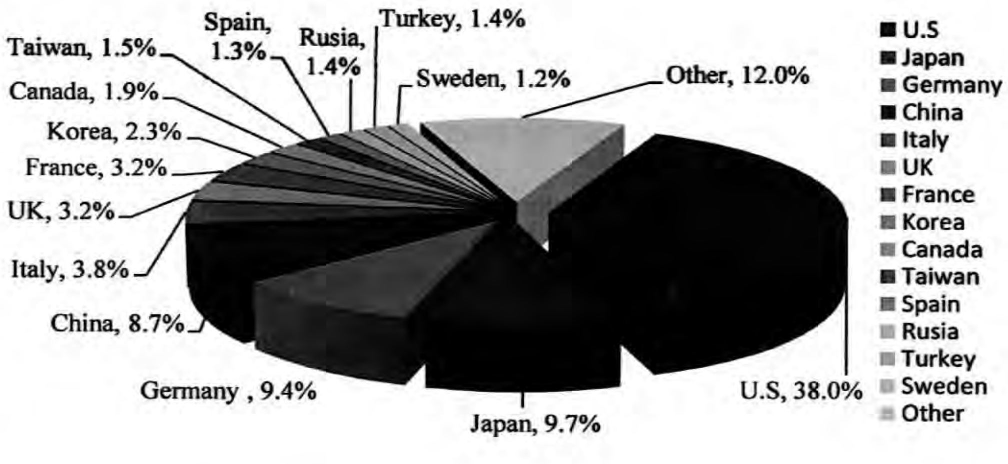


Fig. 1.2 Percentage of industrial AM-systems installed by country [5]

In May 2013, the US government, the country with the highest amount of AM technologies, launched manufacturing hubs and announced the creation of a manufacturing innovation institute. This institute is the National Additive Manufacturing Innovation Institute (NAMII), which focuses on the use of AM to spearhead the development of the manufacturing industry and encourage research throughout the country [6]. Whilst in Japan, the Japanese Economy, Trade and Industry Ministry has started promoting AM and plans to launch new research and development initiatives for the development of AM systems capable of producing metal products in order to ensure its manufacturing competitiveness globally [7][8]. These initiatives taken by the economic giants, are believed to be driven by the immense benefits of AM. Some of the advantages of AM are

- Rapid product introduction into the market
- Customized design and mass customization
- Low cost, in the long term, due to reduced inventory
- Increased design complexity of what can be manufactured
- Less wastage

Despite its advantages, as a relatively new manufacturing technology, AM faces stern challenges before it can be adopted for mass production in manufacturing industries. Some of these challenges are exacerbated by technical obstacles [9]. According to the report, the areas that still need further study are material characterization, material development, process understanding (such as deformation problems, balling and porosity), simulation, part strength and dimensional accuracy. The low number of engineer specializing in this new technology means that technical obstacles directly apply to its industrial application. This is because prior training is needed to operate AM systems. For the initial installation of AM systems in any industry, the setup costs are relatively expensive. There is hesitation on the part of investors who are not aware of the potential of the technology. Other than that, design for manufacturing (DFM) with an emphasis on AM is not a well-developed sector. Since collaboration between industries is crucial, international standards need also to be established [10]. Although there are some preliminary standards produced by the American Society of Mechanical Engineers (ASME), which cover the different aspects of AM, such as terminology (ASTM F2792 - 12a), design (ISO/ASTM52915 – 13), testing methods (ISO/ASTM52921 – 13) and others. Further standard concerning AM will enhance collaborative design and development among AM users as variety of material and processes are being developed. Despite these challenges, AM technologies are currently increasingly gaining in attention from the manufacturing community and academia worldwide. Therefore, the above-mentioned challenges offer a high prospective for opportunities for research and development. However, there are many technical issues that need to be resolved before the technology is mature enough to be adopted for mass production.

There are many variations of AM processes that have existed since its first introduction. Each process has some unique operating principle and application, which offers its own advantages and disadvantages. Among these processes, Selective laser sintering/Selective laser melting (SLS/SLM) shows high potential for the development of functional products. SLS/SLM is a direct fabrication of near net shape products. SLS/SLM is one of the most promising AM techniques and is widely accepted by the industrial community compared to other competing AM technologies. This is due to its high flexibility in processing different types of materials under various conditions with relatively reasonable material properties [10],[11]. Generally, SLS/SLM has improved the lead-time from design to manufacture in comparison to the classical method. However, there is still the same problem as with other AM processes, namely, that the parts produced with SLS/SLM systems still do not meet some of the stringent quality issues and requirements that are necessary if they are to be adopted as a good alternative to the conventional method. The capability of producing an end product of desirable quality compared to traditional processing techniques, has still not been achieved [12],[13].

In the SLS/SLM process, a thin layer of powder is deposited, and laser irradiates the powder surface successively until the final product is produced. The iterative process of powder deposition, laser irradiation and molten powder solidification mean the powder metals consolidate based on the CAD data. The product is a consolidated material the properties of which are influenced by metal powder and processing parameters. SLS/SLM involves the consolidation of metal powder under the influence of a high heat that is generated from laser irradiation over a very short space of time. As a result, the powder and consolidated structure experience repetitive microstructural and behavioral changes. This is because the sintering/melting and solidification occur alternately during layer-by-layer laser irradiation.

Furthermore, the consolidation characteristics of metals produced using SLS/SLM are relatively important due to its application in mold design and manufacturing. Therefore, outstanding properties and high-accuracy are vital characteristics that need to be improved for its application in mold manufacturing. The very basic element of developing a good-quality product is understanding the transformation process of the metal powder to the consolidated structure. This transformation occurs after the metal powders are irradiated with a reasonable amount of heat. Understanding the consolidation characteristics is the key to developing a good structure. This enables controlling mechanisms and methods to be implemented so that future development is possible. In order to improve these aspects, it is important to understand the consolidation characteristics and mechanisms during SLS/SLM.

A lot of research has been conducted into the consolidation characteristics during SLS/SLM. The consolidation mechanisms of metal powder can be classified into liquid phase sintering, solid-state sintering, full melting and chemical induced binding [13]. The binding mechanism in the full melting is mainly influenced by the fluid behavior. This is related to the surface tension, viscosity, wetting, evaporation and oxidation [3]. The ability of the metal powder to consolidate during SLS/SLM depends on many factors. These factors affect the quality and mechanisms involved in the formation of a consolidated structure. They can be categorized into processing factors and material factors. Material factors include the size of the metal powder, its impurities, particle shapes (dendrite or irregular), mixture, chemical composition, homogeneity, degree of agglomeration and others. Whereas, the factors associated with its processing are the laser parameters, processing environment, pressure, processing temperature, cooling rate, time and others. Elsen mentioned that there are more than 50 factors which affect the SLS process [14]. However, from among these parameters, the most important factors are laser power, laser spot size, powder layer thickness, laser scan speed and hatching size [15],[16],[17]. Therefore, a physical understanding and observation of laser beams and material interaction with respect to these parameters are important in SLS/SLM research.

1.2 PROBLEM STATEMENT

Earlier studies which carried out real time observations of SLS/SLM processes using various imaging systems did not produce clear results. This is partly due to the nature of the SLS/SLM whereby the consolidation occurs at a micron scale at very high temperatures. Furthermore, the latest study also suggested carrying out a detailed study into the mechanisms formation of a single track formation and the instabilities of the molten pool that are required for the use of a wider range of commercially available powders is feasible [18]. Hence, a clear and real time monitoring of the consolidation process in SLS/SLM is essential.

SLS/SLM is a complex process as it involves a laser–material interaction process before the consolidated structure is fabricated. During laser irradiation on metal powder, phenomena such as absorption, reflection and heat transfers between different mediums occur. This involves conduction, radiation, convection, phase transformation and chemical reactions taking place. As a result, the laser irradiated region experiences heating, sintering/melting and solidification. Therefore, thermal conductivity is an important thermo physical property in SLS/SLM, which needs to be extensively studied. This is because the ability of the metal powder to conduct heat affects the consolidation process.

As a relatively new process, using a wide variety of materials, the behavior and performance of consolidated materials in SLS/SLM are of utmost importance. Furthermore, since the SLS/SLM process is based on the transformation of metal powders at high temperatures, information on the temperature during SLS/SLM is important. During SLS/SLM processing, the continuous heating and solidification of metal powder within a very short period of time takes place. Hence, the evolution and profile of the temperature in SLS/SLM has a significant effect on the final quality of the consolidated products. Temperature measurement enhances better understanding of the interaction between the powder material and the laser beam [10]. However, few studies have been carried out to measure temperature during SLS/SLM.

1.3 RESEARCH OBJECTIVES

This research focuses on understanding the consolidation behavior of a product manufactured using the SLS/SLM process. In order to understand this, the thermal conductivity of the metal powder, the consolidation characteristics during laser irradiation and the properties of the structure are essential. Although the SLS/SLM process has already demonstrated its ability to successfully develop a final product, the structure formation and irregularities of droplets known as balling, porosity and surface quality are still not understood. Furthermore, triggering mechanisms that causes the metal powder to consolidate is the main area of interest for SLS/SLM. This enhances understanding of the SLS/SLM process.

The objectives of the research are

a. To study the influence of powder particle size, bulk density and powder mixture on the thermal conductivity of metal powder.
b. To analyze the sintering/melting temperature during SLS/SLM process.
c. To design and develop a methodology that allows for the monitoring of the consolidation process of metal powder during SLS/SLM.
d. To understand the characteristics and mechanisms of SLS/SLM during laser irradiation on a metal powdered surface.
e. To investigate the properties of a consolidated material and its potential to develop a permeable structure.

1.4 THESIS OUTLINE

The thesis is divided into seven chapters as follows.

Chapter 1 is an introduction to the research, which covers the background, research objectives and scope of the research work.

Chapter 2 provides an overview of trends in additive manufacturing and its application in the manufacturing industry. The basic principles and different types of AM are described with an emphasis on SLS/SLM. After this, a literature review related to the research is discussed.

Chapter 3 describes the thermal conductivity of metal powders and consolidated structures due to their importance in heat transfer.

Chapter 4 discusses temperature measurements taken during the consolidation process. A pyrometer was utilized to measure the temperature and the effect of laser power and scan speed on the temperature is considered.

Chapter 5 presents the consolidation behavior of the metal powder as the laser beam irradiates it. A high-speed camera was utilized in order to monitor the consolidation at a magnified view during the consolidation process. Based on this, consolidation behavior is presented.

Chapter 6 examines the properties of consolidated structures manufactured using SLS/SLM. As these structures are characterized by the existence of porosity, their potential for use as a permeable structure is investigated.

Chapter 7 concludes the study and highlights further work that can be conducted based on the results attained.

REFERENCES

[1] H. Kodama, "Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer," *Rev. Sci. Instrum.*, vol. 1770, no. 52, 1981.

[2] T. Wohlers, *Wohler Report 2011*. Wohlers Associates, 2011.

[3] J. P. Kruth, G. Levy, F. Klocke, and T. H. C. Childs, "Consolidation phenomena in laser and powder-bed based layered manufacturing," *CIRP Ann. - Manuf. Technol.*, vol. 56, no. 2, pp. 730–759, Jan. 2007.

[4] The Economist, "A Third Industrial Revolution," pp. 1–2, Apr-2012.

[5] T. Wohlers, *Wohlers Report 2013: Additive Manufacturing and 3D Printing State of the Industry*. Wohlers Associates, 2013.

[6] "Obama Administration Launches Competition for Three New Manufacturing Innovation Institutes," *The White House, Office of the Press Secretary*, 2013. [Online]. Available: http://www.whitehouse.gov/the-press-office/2013/05/09/obama-administration-launches-competition-three-new-manufacturing-innova. [Accessed: 25-Nov-2011].

[7] "METI Journal : 3D Printer," *Ministry of Economy, Trade and Industry Japan*, 2013.

[8] Reno J. Tibke, "Japan's 3D Printing Industry," *Akihabara News*, 2013. [Online]. Available: http://akihabaranews.com/2013/08/26/article-en/japans-3d-printing-industry-leapfrog-not-catch-game-play-41031748. [Accessed: 20-Nov-2013].

[9] D. L. Bourell, M. C. Leu, and D. W. Rosen, *Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing*. The University of Texas at Austin, Laboratory for Freeform Fabrication, Advanced Manufacturing Center, 2009.

[10] J. P. Kruth, X. Wang, T. Laoui, and L. Froyen, "Lasers and Materials in Selective Laser Sintering," *Assem. Autom.*, vol. 23, no. 4, pp. 357–371, 2003.

[11] S. Kumar, "Selective laser sintering: A qualitative and objective approach," *JOM*, vol. 55, no. 10, pp. 43–47, Oct. 2003.

[12] E. N. Hopkinson and P. M. Dickens, *An Industrial Revolution for the Digital Age*. John Wiley & Sons, Inc, 2006.

[13] J. P. Kruth, "Material Incress Manufacturing by Rapid Prototyping Techniques," *CIRP Ann. - Manuf. Technol.*, vol. 40, no. 2, pp. 603–614, 1991.

[14] M. Van Elsen, F. Al-Bender, and J. P. Kruth, "Application of dimensional analysis to selective laser melting," *Rapid Prototyp. J.*, vol. 14, no. 1, pp. 15–22, 2008.

[15] A. Simchi and H. Pohl, "Effects of laser sintering processing parameters on the microstructure and densification of iron powder," *Mater. Sci. Eng. A*, vol. 359, no. 1–2, pp. 119–128, Oct. 2003.

[16] S. Dingal, T. R. Pradhan, J. K. S. Sundar, A. R. Choudhury, and S. K. Roy, "The application of Taguchi's method in the experimental investigation of the laser sintering process," *Int. J. Adv. Manuf. Technol.*, vol. 38, no. 9–10, pp. 904–914, Aug. 2007.

[17] A. N. Chatterjee, S. Kumar, P. Saha, P. K. Mishra, and A. R. Choudhury, "An experimental design approach to selective laser sintering of low carbon steel," *J. Mater. Process. Technol.*, vol. 136, no. 1–3, pp. 151–157, May 2003.

[18] I. Yadroitsev and I. Smurov, "Selective laser melting technology: From the single laser melted track stability to 3D parts of complex shape," *Phys. Procedia*, vol. 5, pp. 551–560, Jan. 2010.

CHAPTER 2 : OVERVIEW OF ADDITIVE MANUFACTURING

2.1 INTRODUCTION

In the current scenario of global, fast-paced and competitive world market, ability to manufacture the high-quality products at reduced cost and achieve customer satisfaction is essential. Other than that, product manufacturers are also trying to shorten new-product development time as a mean to gain competitiveness. Hence, the product development time becomes a key differentiator for success of a product in the consumer market.

AM is seen as one of the future technologies that able to compete against traditional processing techniques with its distinctive capability of fulfilling the design requirement. Initially AM technology was used as part of the product design and development process where the prototype of a product was fabricated during visual inspection and design verification stage. However, with the advent of technology, its application extends from merely prototyping to manufacturing. Currently, a number of manufacturers utilize the AM systems to manufacture the final products, although the technology is still undergoing extensive research and development (R&D) and have not achieved its maturity stage.

2.2 RAPID PRODUCT DESIGN AND DEVELOPMENT

AM technology enables transition of computer-aided design (CAD) data to a real product in a shortened time. This leads to significant improvement in the product-development process. Therefore, it is often called as a tool for rapid product design and development. During its early development, AM technology was used to manufacture prototype before its introduction in the market. Later, AM technology was adopted for manufacturing of complex parts and customized design. Fig. 2.1 illustrates product design and development cycle through concurrent engineering approach, which includes the creation of prototypes as one important stage.

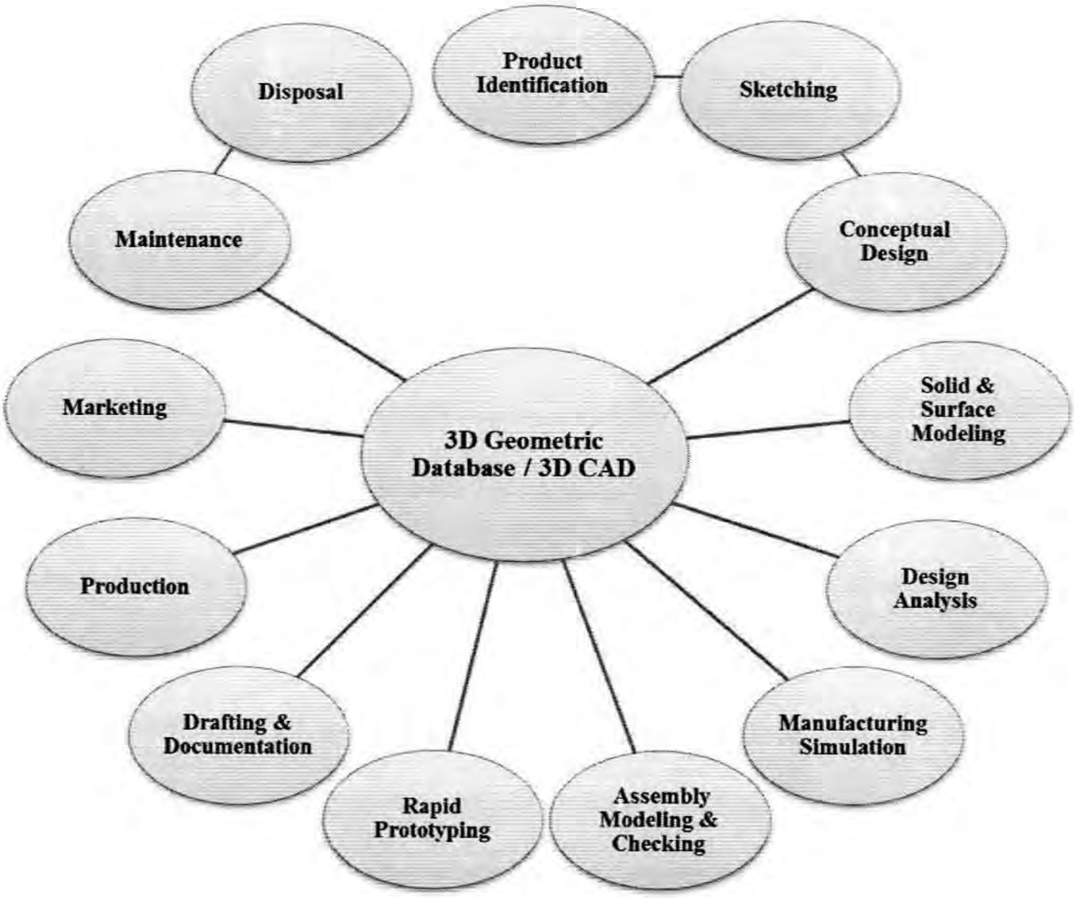


Fig. 2.1 Product design and development cycle through concurrent engineering [1]

There are several terms used to refer the group of AM technologies. Terms used to refer to these technologies are rapid prototyping (RP), layered manufacturing (LM), rapid manufacturing (RM) and 3D printing. Other less common used terms are also used to represent the similar technology; such as solid freeform fabrication (SSF), material addition manufacturing, material incress manufacturing, desktop manufacturing, additive fabrication, direct digital manufacturing, instant manufacturing, direct CAD manufacturing, and others. These terms evolved since the introduction of the technology. For instance, during early development of AM, the term RP is the most common used since it extensively being in producing prototypes. In fact, RP refers to a group of processes where the manufacturing of three-dimensional part from CAD through additive approach [2].

Later, the term of rapid tooling (RT) was used due to increasing application of AM in the mold design and development. This is also driven by increasing utilization of metal in AM. As a result, the common term RP starts to evolve to RT, which reflects its capability to produce mold and tool in a shortened time compared to the classical subtractive method. Nevertheless, not all AM processes directly start a started as RP. One of the examples is laser cladding. Initially, during its early development, laser cladding was mainly used in corrosion-resistant coating and parts refurbishment [3]. However, its application later extends beyond to cover different applications, including RM.

Hence, RT is a progression from the development of RP technologies. Through RT, tool prototype can be directly produced from the CAD model. One of the principal advantages of employing RT is it capable of shortening the tooling lead time from months to a few days or weeks depending on the complexity of the tooling. Since mold making for both prototype and production component manufacturing currently represents one of the longest and most costly phases in the product-development process, application of RT able to improve product development time. However, recently, the term AM is more common as to reflect the generic term used to represent the group of this technology and its potential. Application of AM by manufacturing product and tooling directly from digital CAD to a usable product is a significant move towards reducing time to market and product cost. As a result, an increasing number of industries start to employ AM technologies. This trend has a dramatic impact on the product-development process.

2.3 BASIC PRINCIPLES AND TYPES OF ADDITIVE MANUFACTURING

In AM, the basic principle is the model initially generated from three-dimensional (3D) CAD before part manufacturing. After that, the part is fabricated by the addition of the material layer by layer. Generally, AM undergone common stages before a part can be successfully manufactured. Initially, a part is designed using CAD software. The format of the part design is converted to standard triangulation language (STL) file, which is the standard format in AM file conversion. The STL file is transferred to AM machine. Based on the types of AM systems used, proper machine setup to be performed prior to a fabrication process. After that, the fabrication processes start. Once the fabrication process completed, the part is removed from the fabrication chamber. Depending on the AM systems used, post-processing may be required before the part fit enough and ready to be used. Fig. 2.2 illustrates the basic principles and stages of AM in product development.

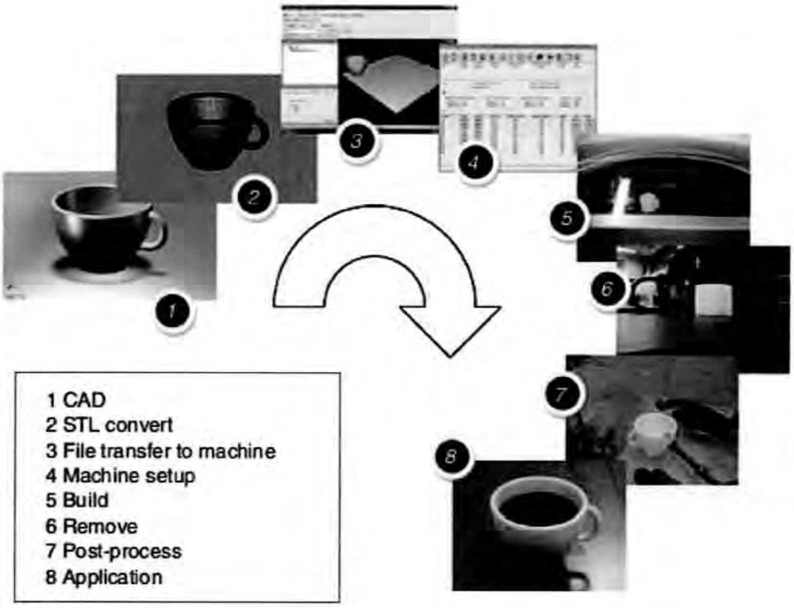


Fig. 2.2 Basic principle and stages in AM [4]

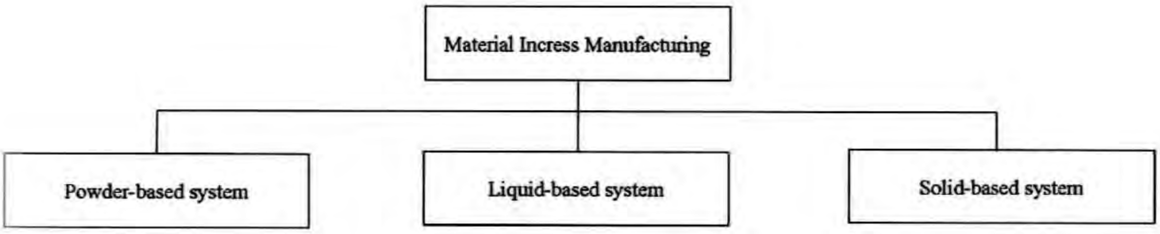
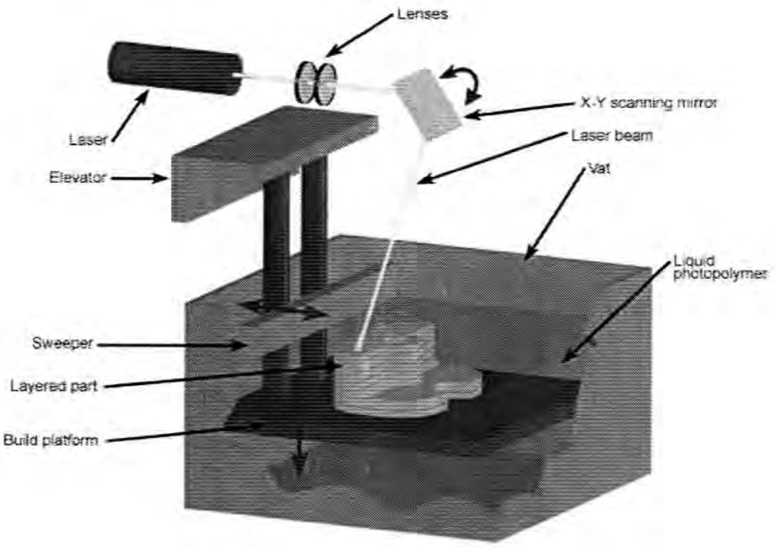


Fig. 2.3 Classification of material incress manufacturing [5]

There are many types of AM processes available. The AM can be classified based on the state of raw material input, baseline technology used and methods of the layer construction [4],[5],[6],[7]. However, among various classifications proposed by AM researchers, the most common classification of AM based on the properties of the initial form of the main material input used during processing. The classification was proposed by Kruth [5] and is shown in the Fig. 2.3. The author used the term material incress manufacturing to describe relatively similar technology, which then evolve to AM. This classification can be divided into powder-based systems, liquid-based systems and solid-based systems. Each of the systems can be further divided as illustrated in the figure.

2.3.1 Liquid-based AM

Liquid-based AM means the initial form of material input to produce the part is in the liquid state. Common materials used are thermoplastic polymers and thermosetting polymers such as polyamide nylons and epoxies respectively. The parts manufactured via the liquid-based systems AM undergone curing process where the liquid is solidified producing 3D solid part. Some of the examples are Stereolithography (SLA), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC), Solid Creation System (SCS) and others [2][8].



Copyright © 2008 CustomPartNet

Fig. 2.4 Liquid-based AM - Stereolithography (SLA)[9]