SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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EFFECT OF FUSED DEPOSITION MODELLING FABRICATION PARAMETERS ON THE TENSILE PROPERTIES OF ACRYLONITRILE BUTADIENE STYRENE

By

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DECLARATION

I hereby declare that I have conducted, complete the research work and written the dissertation entitled **“Effect of Fused Deposition Modelling Fabrication Parameters on the Tensile Properties of Acrylonitrile Butadiene Styrene”**. I also declared that it has not been previously submitted for the award for any degree or diploma of other similar title of this for any other examining body or University.

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LIST OF ABBREVIATIONS

Abbreviation	Description
1D	1-Dimensional
2D	2-Dimensional
3D	3-Dimensional
3D Printing	3-Dimensional Printing
AM	Additive Manufacturing
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BISO	Bilinear Isotropic Hardening
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CLS	Cellular Lattice Structures
CNC	Computer Numerical Control
DOE	Design of Experiment
EBM	Electron Beam Melting
Et	Elongation at Break
FDM	Fused Deposition Manufacturing
FEA	Finite Element Analysis
FEM	Finite Element Method
IS2	IRT Cronista Infrared Image
JPEG	Joint Photographic Experts Group
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
MISO	Multilinear Isotropic Hardening
MSDS	Material Safety Data Sheet

R	Raster Orientation
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
SD Card	Secure Digital Card
SEM	Scanning Electron Microscopy
SFF	Solid Freeform Fabrication
SL	Stereolithography
SLS	Selective Laser Sintering
STL	Standard Tessellation Language
T	Printing Temperature or Temperature
TS	Tensile Strength
TGA	Thermogravimetric Analysis
UV	Ultraviolet

LIST OF SYMBOLS

Symbol	Description
$\dot{\varphi}$	Plastic Multiplier
σ	Stress
σ_{ij}	Stress Tensor
$\dot{\sigma}$	Stress Rate
$\ddot{\sigma}$	Objective Stress Rate
ε	Strain
$\dot{\varepsilon}_{ij}$	Strain Rate
ψ	Deformation Constant
Ω	Rotational Rate
$\frac{\partial \sigma_{ij}}{\partial x}$	Partial Differential
b_i	Body Acceleration Components
D	Total Deformation Rate/Nodal Displacement
D_p	Plastic Deformation Rate
D_e	Elastic Deformation Rate
$\dot{e}$	Conservation of Energy
E	Young’s Modulus
F	Nodal Force
F_i	Nodal Force
I	Identity Tensor
K	Stiffness Matrix
m	Mass of Node or Element
n	Integer
ρ_o	Initial Density

t	Time
$tr\,(\,)$	Tensor Trace
μ	Poisson’s Ratio
V_o	Initial Volume
V	Volume
$\dot{x}_i$	Nodal Velocity with (i=1,2,3)
$\ddot{x}$, $\ddot{y}$, $\ddot{z}$	Acceleration in x-, y-, z- directions
$\ddot{x}_i$	Nodal Acceleration Components with (i=1,2,3)

KESAN PARAMETER PERMODELAN ENAPAN TERLAKUR KE ATAS SIFAT-SIFAT TEGANGAN ACRYLONITRIL BUTADIENA STIRENA

ABSTRAK

Dalam kajian ini, kesan orientasi *raster* ($0^o/90^o$, $30^o/120^o$ dan $45^o/135^o$) dan suhu percetakan (220^oC, 230^oC, 240^oC dan 250^oC) permodelan enapan terlakur (FDM) ke atas sifat-sifat tegangan Acrylonitrile Butadiene Styrene (ABS) telah dikaji. Spesimen FDM telah dihasilkan dan dimodel mengikut piawaian ASTM D638 Jenis I untuk kedua-dua ujian mekanikal dan analisis unsur terhingga (FEA) dengan menggunakan perisian ANSYS. Sifat-sifat tegangan telah diukur dan digunakan selanjutnya dalam FEA. Ciri-ciri permukaan patah spesimen diperiksa dengan menggunakan *tabletop scanning electron microscope* (SEM). Analisis kestabilan haba ABS juga dijalankan dengan menggunakan analisis termogravimetrik (TGA) dari suhu bilik kepada 250^oC. Lengkungan tegasan-terikan, kekuatan tegangan, *elongation at break*, dan modulus Young telah dianalisi. Ia dapat diperhatikan bahawa kesan orientasi *raster* dan suhu percetakan amat signifikan ke atas sifat-sifat tegangan sampel ABS yang dihasilkan. Penghasilan ABS melalui FDM telah menunjukkan kelakuan mulur dan ia semakin ketara daripada orientasi *raster* $0^o/90^o$ kepada $45^o/135^o$. Permukaan patah ABS yang licin dan rata pada orientasi *raster* $0^o/90^o$ dan suhu percetakan 220^oC, 230^oC dan 250^oC telah menunjukkan kegagalan rapuh. Manakala permukaan patah yang kasar dan tidak sekata dalam ABS dihasilkan pada orientasi *raster* $30^o/120^o$ dan $45^o/135^o$ dan suhu percetakannya 240^oC, di mana ia menunjukkan kegagalan mulur. Kestabilan haba ABS pada 250^oC telah dibuktikan adalah rendah. Sifat-sifat tegangan yang terbaik telah dijumpai pada orientasi *raster* $0^o/90^o$ dan suhu percetakan 240^oC. Ia juga mendapati bahawa simulasi ANSYS telah menunjukkan persetujuan yang baik dengan keputusan eksperimen dan mampu meramal kelakuan tegangan ABS yang dihasilkan melalui FDM.

EFFECT OF FUSED DEPOSITION MODELLING FABRICATION PARAMETERS ON THE TENSILE PROPERTIES OF ACRYLONITRILE BUTADIENE STYRENE

ABSTRACT

In this study, the effect of raster orientation (0°/90°, 30°/120° and 45°/135°) and printing temperature (220°C, 230°C, 240°C and 250°C) on the tensile properties of fused deposition modelling (FDM) fabricated acrylonitrile butadiene styrene (ABS) were investigated. The FDM specimen was fabricated and modelled according to the ASTM D638 Type I for both mechanical test and finite element analysis (FEA) using ANSYS software. Tensile properties were measured and employed further in FEA. The morphological characteristics of the fractured surface of specimens were examined using tabletop scanning electron microscopy (SEM). Thermal stability analysis on ABS was also done using thermogravimetric analysis (TGA) from room temperature to 250°C. The stress-strain curve, tensile strength, elongation at break, and Young's modulus were analysed. It was observed that significant influence of raster orientation and printing temperature of FDM on tensile properties of the produced ABS samples. The FDM fabricated ABS exhibited slightly ductile behaviour and becoming more obvious from 0°/90° to 45°/135°. The fractured surfaces of ABS fabricated at 0°/90° raster orientation and 220°C, 230°C and 250°C printing temperature were smooth and flat, which indicated brittle failure. Meanwhile, ABS fabricated at 30°/120° and 45°/135° raster orientation and 240°C printing temperature had rough and irregular fractured surface, which indicated ductile failure. Thermal stability of ABS at 250°C was proved to be low. The best tensile properties were found to be at raster orientation of 0°/90° and printing temperature of 240°C. It also observed that ANSYS simulation has good agreement with experimental result and able to predict the tensile performance of FDM fabricated ABS.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter will provide an insight on the significant of this research. It covers the research background, problem statement, research objectives, approach and scope of this study. The study background on the additive manufacturing will provide an overview on the overall topic that will be discussed throughout the thesis. The problem exists in this field of study is highlighted in the problem statement, while the objectives to be achieved in this study are conveyed. The research approach to achieve the outlined research objectives is presented. The following subtopic will discuss about the scope of study with elaboration. Lastly, the overall thesis outline is simplified in the last part of this chapter.

1.2 Background Study on Additive Manufacturing

Additive manufacturing (AM) is the formal term used to describe rapid prototyping (RP), which is also known as 3-dimensional printing (3D printing). 3D printing has been traditionally been used for AM, with the primary intention of fabricating models for visualization, design verification and kinematic functionality testing on developing assemblies (Ziemian et al., 2012). AM describes a rapid process to create a system or part representation before commercialization. It is an innovative technology to produce a 3-dimensional (3D) part directly from a predesigned digital model, under control of software.

Regardless of the complexity of the part geometry, a high-quality part, prototype or product can be easily produced using AM technology, in relatively short time, low production cost and less material wastage (due to less product failure or less product flashing). The printable digital models can be created with a computer-aided design

(CAD) package, such as 3D scanner, plain digital camera and photogrammetry software (Jacobs, 1992). CAD software will help to detect and correct the design errors, before building process. This is vital to ensure precise and smooth printing process, as it involves fabrication of material layer by layer. Any misalignment in the digital model will affect the product properties, performance, quality and appearance.

AM process is widely used in manufacturing, medical, and sociocultural sectors. The earliest AM technology was used on the toolroom end of the manufacturing spectrum (Taufik and Jain, 2016). Recently, this technology is also applied in food industry to produce food into a variety of 3D geometries, clothing sector, automotive and aircraft industries (Richter and Lipson, 2011). This technology offers a variety of advantages as compared to the conventional plastics processing technologies. First, it enables mass customization of product, increases design freedom, reduces the tooling or assembly, and serves as a cost-effective low-volume production process.

AM is also known as solid freeform fabrication (SFF) process help to overcome the general problems in building complex shapes model or product, by building material in layers. The parts can be of any shape or geometry and it will be printed in one part, requiring no additional tooling or assembling (Zou et al., 2016). Among all the different AM processes, it actually can be classified into liquid-based, solid-based, and powder-based processes, as shown in Figure 1.1. The techniques considered include stereolithography (SL), polyjet, fused deposition modelling (FDM), laminated object manufacturing (LOM), 3-dimensional printing (3DP), prometal, selective laser sintering (SLS), laser engineered net shaping (LENS), and electron beam melting (EBM). The concept applied is different for each process. For example, melting event is used in the liquid-based FDM technique and powder-based SLS, EBM and LENS techniques, while polymerization concept is applied in SL and polyjet techniques.

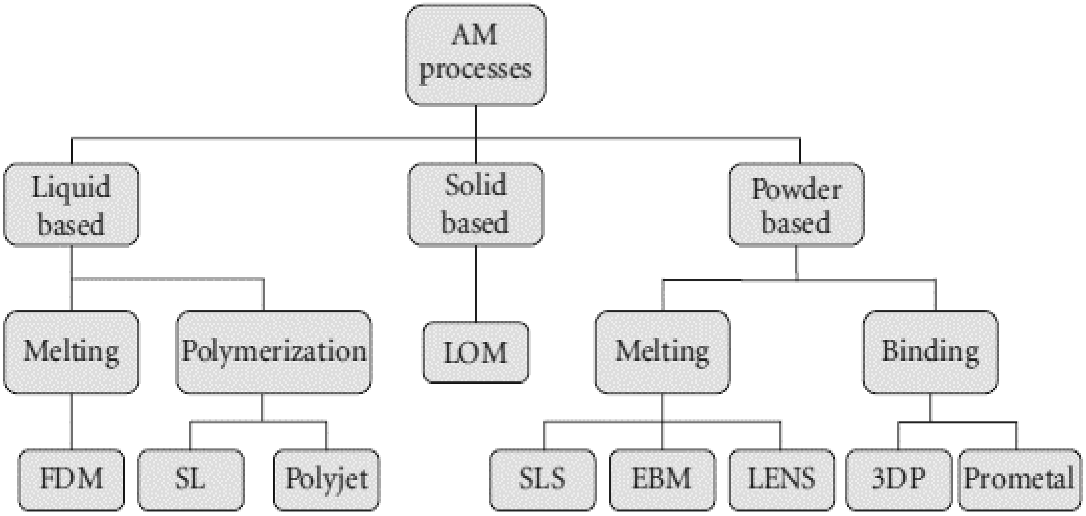

Figure 1.1: Classification of AM technology (Wong & Hernandez, 2012).

The liquid- and powder-based AM processes are more predominant than solid-based processes. In 2004, EBM, prometal, LENS and polyjet were no longer been employed in research and industry (Wong & Hernandez, 2012). Among the AM processes, the two most common technologies are SLS and FDM. The SLS applies high-power laser to fuse powder particles of metal, ceramic, glass or plastics into a mass that has desired 3D shape. Meanwhile, FDM utilizes thermoplastic filament injected through nozzles onto a platform (Attaran, 2017). Both techniques have its own unique set of competencies and limitations. However, FDM is the most widely used technique as compared to SLS due to its reliability, low cost and low material wastage.

Since FDM technique applies material melting concept for part fabrication, the type of printable materials includes plastics, resins, rubbers, ceramics, glass, concretes, and metals. However, the most widely used printing materials are thermoplastics. This is because they can be pre-processed in form of filament and be thermo-softened or melted upon heating up to a specific temperature, then it can solidify upon cooling. This melting-cooling event can happen up to several times. Its thermo-softening behaviour eases the feeding-material preparation and also FDM printing process. Although all thermoplastics can be extruded into filament, but not all thermoplastic materials can be printed using FDM technique. Another attention to be paid on FDM technique is the mechanical properties of FDM fabricated part. Similar to the conventional fabrication techniques such as injection moulding, extrusion, thermoforming, etc, the fabrication parameters will directly affect the mechanical performance of fabricated part.

In the product design and development, finite element analysis (FEA) is getting popular due to its ability to predict the performance of a part in the specified conditions, fluid mechanics, solid mechanics, and structural dynamics (Hutton, 2004). It can help to improve the product design, optimize their performance, predict the service lifetime, and reduce cost somehow. Mechanical performance of part is important to fulfil customers' requirement. Hence, structural dynamics FEA are widely used to determine the properties of part in linear and non-linear deformation, such as tensile properties, compression properties, impact properties, etc.

1.3 Problem Statement

Mechanical properties are the key performance of a printed part or product. There are a variety of interdependent process parameters that have varying extent in affecting its mechanical properties, includes printing orientation, raster orientation, air gap, raster width, filament colour and layer thickness (Zou et al., 2016). However, the orientations, either raster orientation or printing orientation have more significant influence on the mechanical properties of the FDM fabricated part, as compared to other printing parameters. This is because FDM is a solid-based system to deposit a molten plastic filament in the desired orientation and will cause the printed part to have a direction dependent property.

The direction dependent property is due to the anisotropic properties of individual filament, where there is alignment of polymeric chains in the axial direction of filament. During preparation of filament, the long polymer chains in molten state will gain thermal energy and become more mobile. Furthermore, they will be forced to disentangle from each other, slide and align in the flow direction during extrusion. The post-extrusion drawing process has further increased the chain orientation. As a result, chains are rearranged and aligned along the axial axis of filament, gives rise to better mechanical properties of filament in axial direction than transverse direction, due to the difference in extent of chains interaction forces (Chris, 2014). Since the feedstock filament has anisotropy properties at the initial, the orientation of filaments in one certain angle such as all printed in 45^o for one part (for printing orientation) or in two alternative different angles such as 45^o and 135^o for one part (for raster orientation), for sure, will interfere with the mechanical performance (either anisotropic or orthotropic) of the printed part.

At present, numerous researches have been carried out to determine the influence of printing orientation on the mechanical properties of FDM fabricated part. However, little work has been carried out to investigate the influence of raster orientation on the properties of FDM part. Furthermore, there is also very less researchers work on the printing temperature parameter, as compared to others such as air gap, layer thickness, filament colour, etc. In order to fill the research gap, raster orientation and printing temperature will be the core investigation parameters in this research. The research approach is by experimental work and also simulation. This is also because little literatures have reported about the simulation study in FDM and its comparison with the experimental result. Therefore, a simulation and experimental study on the most concerned tensile properties of FDM will be carried out at different raster orientations and printing temperatures. The most widely investigated material Acrylonitrile Butadiene Styrene (ABS) was used in this study too. Comparison between the simulation and experimental works will be made to investigate and correlate the works.

1.4 Research Objectives

This research focuses on the tensile properties of ABS fabricated from FDM, with the following specific research objectives:

a) To investigate the effect of raster orientation and printing temperature on the tensile properties of ABS fabricated from FDM.
b) To simulate the tensile properties of FDM fabricated ABS by FEA computational study.
c) To correlate the experimental and simulated tensile properties of FDM fabricated ABS.

1.5 Research Approach

There are three stages to carry out the research, which are fabrication of tensile specimen using FDM with the desired parameter sets, tensile testing on all specimens, and lastly simulation on the tensile properties of FDM fabricated ABS.

1.6 Research Scope

In this research, the tensile properties of the ABS fabricated from FDM will be investigated. The tensile properties of the fabricated parts will be studied for their stress-strain curve, Young’s modulus, tensile strength, and elongation at break. The main parameter on the tensile properties of the ABS is the raster orientation and printing temperature. Finally, the performance of FDM fabricated ABS in all variable variations will be determined experimentally and computationally through FEA by using ANSYS software. The result will be evaluated and correlated.

1.7 Thesis Outline

This thesis covers five chapters that consists of:

Chapter 1: Introduction to the study background, problem statement, specific research objectives, research approach, research scope and thesis content.

Chapter 2: Detailed literature reviews on the AM technology, its types and advantages, FDM process, the materials used in FDM, mechanical properties of the FDM fabricated parts under different parameters such as printing layer thickness, layer orientation, raster angle, raster width, air gap, etc, and lastly on the FEA study.

Chapter 3: Explanation on the overall research flow, methods used in investigation of the tensile properties of FDM fabricated ABS, the experimental procedures employed, the raw materials, equipment and software involved in generating the data for this research.

Chapter 4: Detailed discussion on the data obtained in form of tables and charts on tensile properties of the FDM fabricated ABS such as stress-strain curve, tensile strength, elongation at break, Young's modulus, stress distribution from FEA, and fractured surface morphology from SEM.

Chapter 5: A short summary and conclusion on the whole research work as well as suggestions for further research.

Chapter 6: A list of references used in this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, a detailed literature review to the background of study on additive manufacturing, types of additive manufacturing process, advantages of additive manufacturing, introduction to FDM process, and finite element analysis will be delivered in the following subsections.

2.2 Additive Manufacturing

AM refers to the technology or the additive process of successive deposition of thin material layers (0.001 to 0.1 inches in thickness) upon each other to produce a 3D product (Attaran, 2017). Over the last thirty years, the contribution of AM on the commercial manufacturing practice has changed enormously and become increasingly prevalent in the industry. Initially, the first form of creating layer-by-layer a 3D prototype using CAD for new products before commercialization was rapid prototyping (RP). The common product development cycle for a new product is shown in Figure 2.1. RP enables fast model and prototype creating to help the realization of the design. It allows the creation of printed parts without purchasing the mould tools or manufacturing machine, which could save a lot of time on product development, cost investment, labour, enable more model testing, and able to create any shape that is very difficult to machine (Wong & Hernandez, 2012).

However, RP is not yet employed in the manufacturing sector at that time. It is commonly used by scientists, medical doctors, students, professors, market researchers, and artists (Wong & Hernandez, 2012). Scientists and students can quickly build and analyse models for theoretical comprehension and understanding. Meanwhile, doctors can build a model for a damaged body to study and plan a better medical procedure.

Next, market researcher can build a model to survey the opinion of people on the new product design. RP can also enable the artists to explore their creativity.

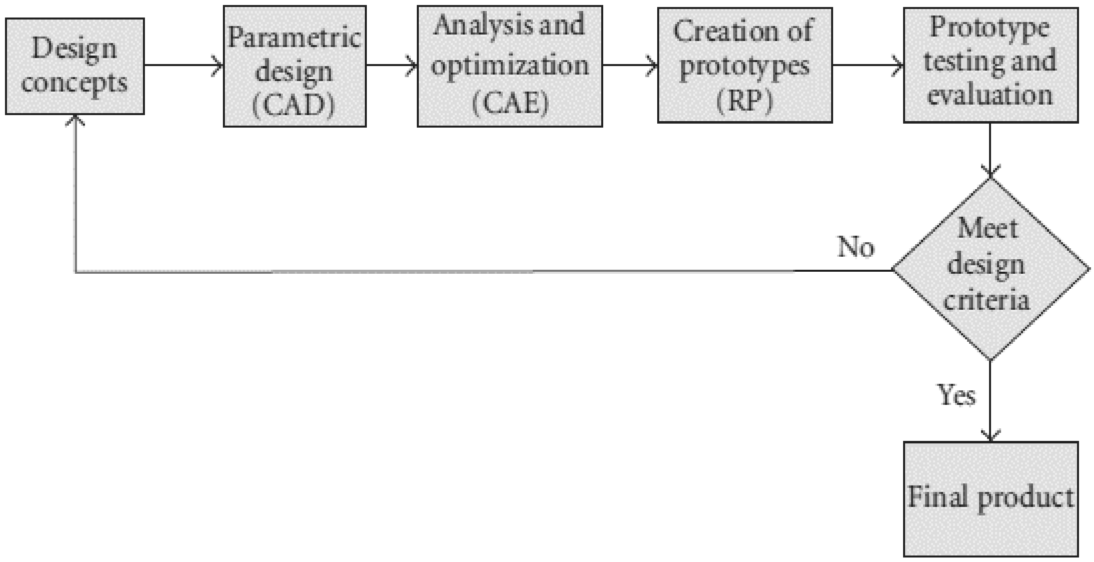

Figure 2.1: The common product development cycle (Wong & Hernandez, 2012).

With the revolution of technologies, the RP application has improved and extended through to tooling. This technology is called “rapid tooling (RT)”. It adopts RP techniques and applies it on tool and die making. Industries are increasingly looking towards RT for short production runs, which do not need huge investment as compared to conventional hard tool making. The application of RT for tool making can be classified into hard or soft tooling and also direct or indirect tooling, as shown in Figure 2.2. Soft tooling refers to tooling for short manufacturing runs, while hard tooling refers to tooling for longer manufacturing runs. Whereas direct tooling refers to the tool is made directly from the RP process and indirect tooling refers to the model created by RP is used in secondary process to produce tool. This pre-series production technology has further shortened the product development cycle by at least half, enable fast production of equipment and tools testing, and also market testing (Chua et al., 1999).

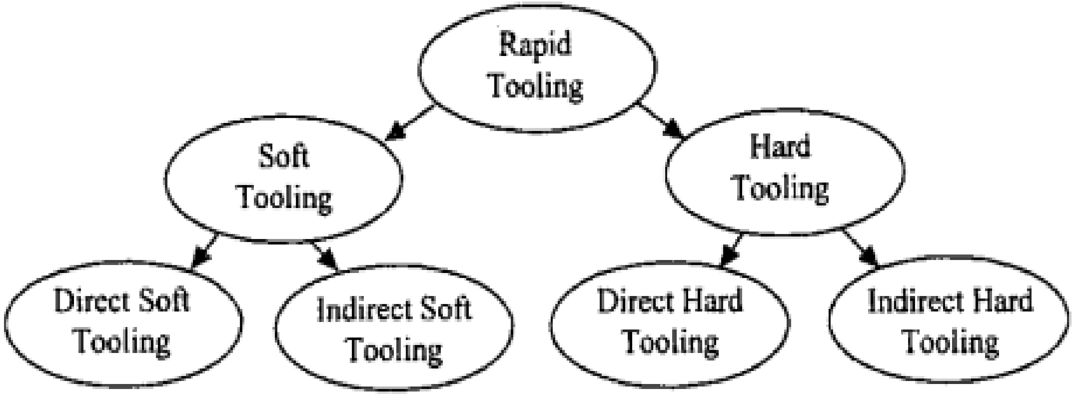

Figure 2.2: Classification of RT (Chua et al., 1999).

The innovation of technology has not only extended AM technology to RP and RT, but also progressed to rapid manufacturing (RM) for direct production of end-use parts or whole products. According to Hopkinson et al. (2006), RM is defined as "the use of a CAD based automated AM process to construct parts that are used directly as finished products or components". RM is made possible by other technologies, such as CAD, computer-aided manufacturing (CAM), and computer numerical control (CNC) (Wong & Hernandez, 2012). With the combination of these three technologies, the 3D parts or whole products can be printed.

AM technologies which have sufficient maturity to be applied in the production of prototypes, tools, parts, or whole products in the industrial manufacturing environment is called industrial AM systems. Table 2.1 shows some of the application of industrial AM for different purposes. They are competitive to the tranditional manufacturing technologies such as injection moulding, extrusion, blow moulding, thermoforming, etc. Table 2.2 summarizes the main industrial AM technologies. These developments may invoke a new industrial revolution with the ability to generate a global economic impact of $200 billion to $600 billion every year by 2025 (Eyers & Potter, 2017).

Table 2.1: An overview on the application of AM in additive manufacturer A, B, C and D for several products (Eyers & Potter, 2017).

Additive Manufacturer	Product Description	AM Application	Variety/Customization
A	In-The-Ear (ITE) Hearing Aid.	RM	High
B	Prototype toothbrush fixture inspection	RP	High
B	Tool prototyping of an exhaust sensor	RT	High
C	Surgical guide customization	RM	High
C	Customization of customer website-designed lighting product	RM	Medium
C	Standardization of professional-designed lighting product	RM	Low
D	Aesthetic Marketing Headphone Model	RP	High
D	Component of automotive	RT	Low

There are four main interelated components in AM technology, includes designing, pre-processing, manufacturing, and post-processing. First, the design component involves the creation of a 3D design model file either by using CAD software packages, reverse engineering by scanning an existing artefact, or derivation from an existing design with configurator software. Second, the pre-processing activities are carried in preparation for manufacturing, which includes manufacturing feasibility evaluations, error checking on the 3D design model, building preparation, and production planning. After pre-processing activities, the output from the first and second components are used to build the parts or whole products using industrial AM machine. Machine-specific setup, material preparation and loading are carried out prior to manufacturing process. Finally, the completed parts or products require post-processing such as product identification, finishing, cleaning, material recovery for recycling, quality checking, and assembly for multicomponent products (Eyers & Potter, 2017).

Table 2.2: An overview of principal industrial AM process types, technologies, manufacturers, and materials (Eyers & Potter, 2017).

Process Type	**Process Description**	**Focal AM Technologies**	**Principal Manufacturers**	**Principal Materials**
Binder Jetting	Selectively deposit liquid binder to join powder materials.	3DP	Z-CORP, 3D Systems, and ExONE	Various powders including metals, sands, metal alloys, etc.
Direct Energy Deposition	Fuse pre-deposited molten materials by focused thermal energy.	Lased Cladding, Laser Metal Fusion, and Laser Metal Deposition	Trumpf	Various metal powders.
Material Extrusion	Selectively disperse material through a nozzle.	Fused Deposition Modelling	Stratasys	Various thermoplastics.
Material Jetting	Selectively deposit droplets of build material.	Multijet Modelling	Stratasys	Ceramics, liquid, photo-sensitive polymers, and waxes
Powder Bed Fusion	Selectively fuse powder bed region by thermal energy.	Selective Laser Sintering (Plastics)	EOS and 3D Systems	Polyaryletherketone, polystyrene, polyamide and various composites.
		Selective Laser Sintering (Metals)	EOS and Renishaw	Various alloys such as cobalt chrome, titanium, stainless steel, etc.
		Selective Laser Melting	ReaLizer	Various alloys such as steel, cobalt chrome, titanium, etc.
		Electron Beam Melting	ARCAM	Various alloys such as Inconel, titanium, cobalt chrome, etc.
		LaserCUSING	Concept Laser	Various alloys such as titanium, bronze, cobalt chrome, etc.
Sheet Lamination	Bond sheet materials to form an object.	Laminated Object Manufacturing	MCOR and EnvisionTEC	Sheet paper and various composite thermoplastics.

2.3 Types of Additive Manufacturing Process

There are few different AM processes, as categorized in Figure 1.1 according to the state of feeding materials used. There are solid-based, liquid-based and powder-based processes. Each process has few different techniques that are going to be further discussed here.

2.3.1 Liquid-Based Additive Manufacturing Processes

A. Fused Deposition Modelling

In FDM process, **s**olid materials in filament form are commonly used. The process starts with melting of filament to 1°C above its melting temperature (so that it can solidify immediately after extrusion and cold welds to previous layers[1]), followed by melt extrusion through the heated nozzle to create a molten road[2] of build material inside the build chamber (Huang et al., 2013). The temperature of the build chamber is maintained just below the melting point of the build material. A controllable nozzle is moved horizontally in the build chamber to deposit the molten road and create an ultra-thin layer in the required 2-dimensional (2D) cross-section profile. After deposition, the molten road will solidify upon adhesion to the previous layer. The adhesion occurs through cold welds on the contact point between layers (Swift & Booker, 2013).

Similarly, the platform is lowered in a distance equals to the thickness of the solidified layer. The process is repeated to build a 3D part. In FDM, a second nozzle can be used to deposit the additional support material for overhangs and undercuts. These features are deposited simultaneously during the deposition process of the main part. The material used for the support features must be soluble in certain solvent as they will be dissolved away after the completed part is removed from the build chamber (Swift &

[1] Layer in FDM refers to all the roads oriented at the same layer or level.
[2] Road in FDM refers to one extruded molten thermoplastic filament from its nozzle.

Booker, 2013), or cheaper and weaker materials that can be broken away from the part without impairing the surface (Huang et al., 2013). The FDM process can be seen in Figure 2.3.

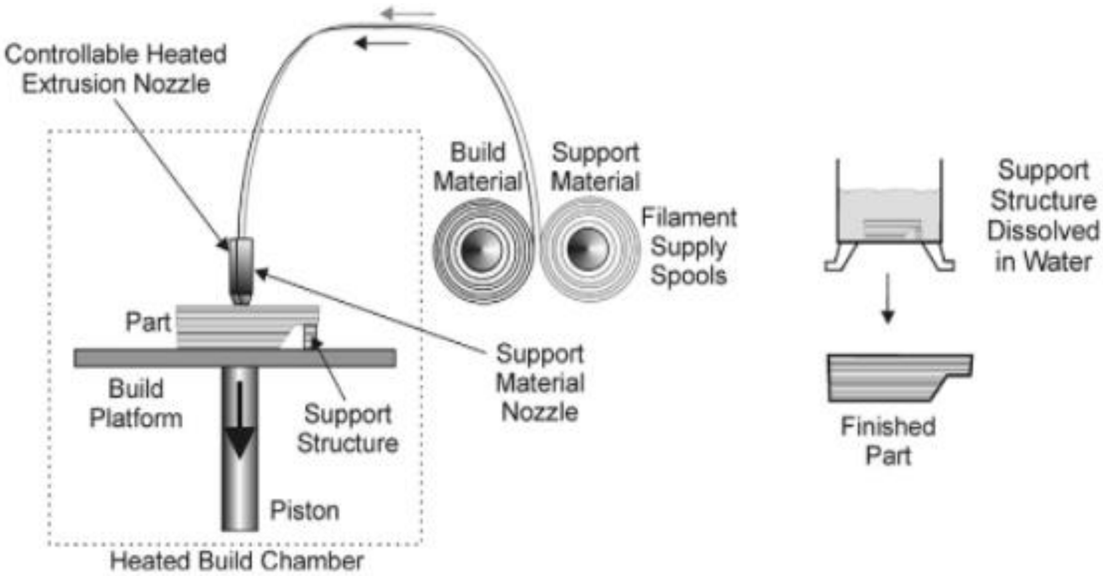

Figure 2.3: Illustration of FDM process (Swift & Booker, 2013).

Ahn et al. (2002) mentioned that to start the FDM process, a 3D digital model must be created using CAD packages. The model will be formatted into standard tessellation language (STL) file format before exporting into the 3D printing software. The STL format will tessellate the model into a set of triangles or rectangles, and the model will be horizontally sliced into many thin sections to represent the 2D contours in x- and y-direction. The software uses this information to generate process plan that controls the FDM machine's hardware. Then the FDM process will generate layer and stack upon one another in z-direction to resemble the 3D part.

B. Stereolithography

In SL process, a mirror is used to reflect and direct the low-power laser beam to the build chamber. Inside the build chamber, a thin 2D cross-section layer of the parts to be produced is traced in a liquid photopolymer resin sealed inside the build chamber. As the polymer is sensitive to laser, photopolymerization occurs to form a hardened and cured 3D pixel of polymer. Due to the absorption and scattering events on the laser beam in air medium, this process only takes place near the surface of photopolymer resin. The platform is lowered down with a distance equals to the thickness of previously cured layer, for more polymer to be formed at the surface of the resin (Swift & Booker, 2013).

In order to replenish another layer of uncured resin on the cured polymer cross-section layer, a sweeper blade moves across it. The laser will trace out the next 2D cross-section layer and the process is repeated to build a 3D part. The cured layers are able to bond together due to the nature adhesive property of polymer. After the 3D part is built, the completed part is drained, washed in suitable solvent to remove the excess resin and subjected to ultraviolet (UV) light for complete curing. Finally, the support constructions are removed by cutting (Swift & ultraviolet Booker, 2013). The process is illustrated in Figure 2.4.

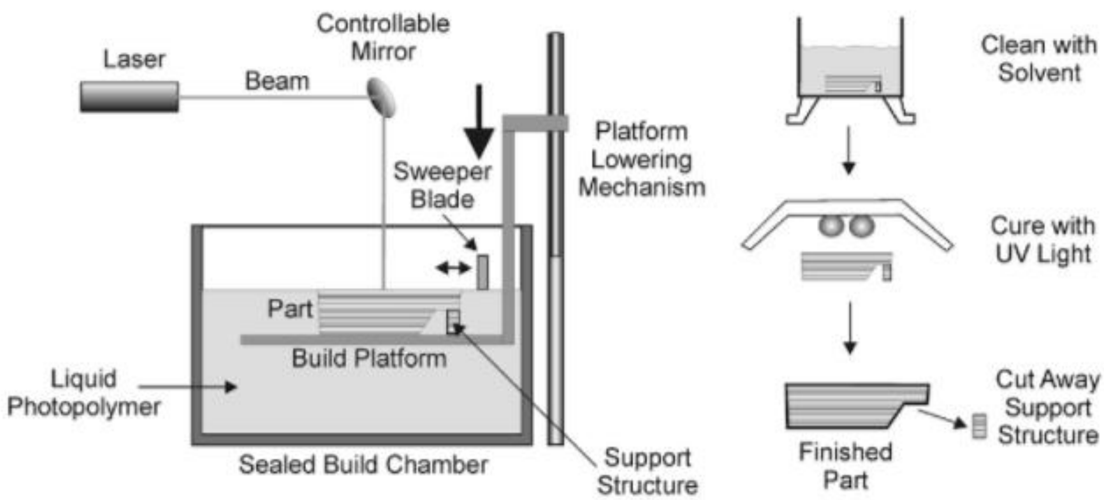

Figure 2.4: Illustration of SL process (Swift & Booker, 2013).

C. Polyjet

In this liquid-based AM process, Polyjet employs inkjet technology to fabricate physical parts. The inkjet head moves in x- and y- axes to deposit a fixed quantity of photosensitive polymer which is then cured using UV light after each layer is finished. The typical layer thickness achieved by this technique is 16 μm, which in turn produce part with high resolution (Wong & Hernandez, 2012). However, the parts produced by this technique are mechanically weaker than parts produced by other techniques such as SL and SLS. To support the overhang features of the part, a gel-type polymer is used, and it is removed via water-jet after the fabrication process is finished. The utilization of inkjet technology enables the part to be fabricated in multiple colours (Udroiu, 2010). Figure 2.5 reveals the Polyjet process.

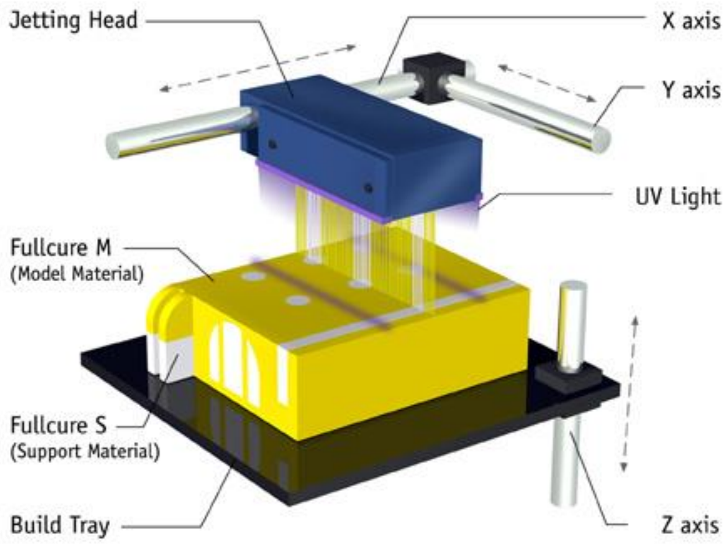

Figure 2.5: Illustration of Polyjet process (Udroiu, 2010).

2.3.2 Solid-Based Additive Manufacturing Processes

A. Laminated Object Manufacturing

In LOM process, a variety of adhesive-coated sheet materials are used such as plastics, paper, metals, fabrics, synthetic materials, and composites. The adhesives are pre-coated onto the sheet or deposited prior to bonding, to allow the sheets to be adhered to each other. The subsequent steps are laminating and cutting of 2D cross-sections using carbon dioxide laser beam (Huang et al., 2013). It cuts the part slice from sheet mounted on a 2D plotter. The velocity and focus of laser beam are adjusted to make sure the cutting depth corresponds to the thickness of the sheet layer. This is vital to prevent damage on the underlying layers since each layer has different 2D cross-sections.

Then, another sheet of materials is stacked on top of each other automatically and bonded together with adhesive. A laminating roller is used to level and compact the sheet stacks. The laminating and cutting processes repeats until a 3D part with the desired shape and dimensions is formed. The part of the sheets located outside the part model tends to provide support and the unwanted areas are marked with intersecting lines, which forms cubes that can be broken away from the model once it is completed (AZoM, 2013). The process of LOM is illustrated in Figure 2.6.

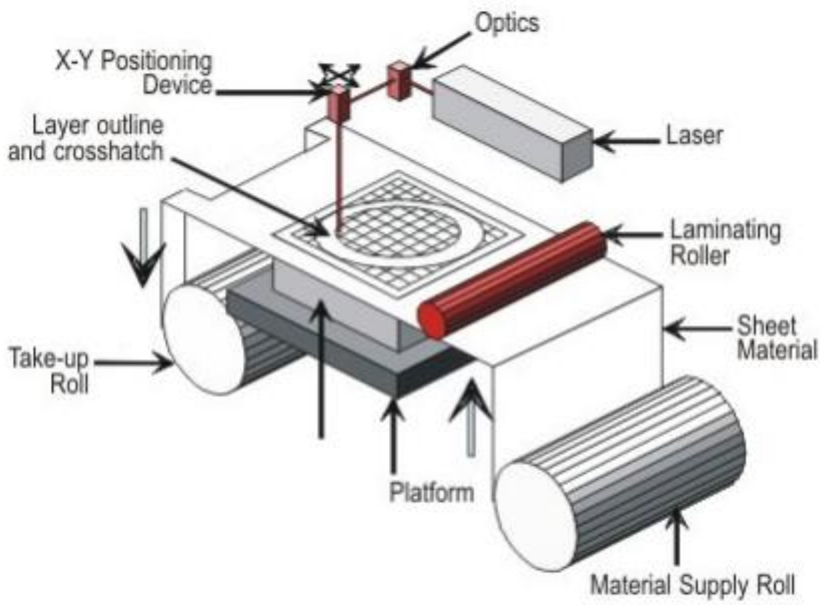

Figure 2.6: Illustration of LOM process (AZoM, 2013).

2.3.3 Powder-Based Additive Manufacturing Processes

A. Selective Laser Sintering

SLS process uses high-power laser beam (range from 7 to 200 W) directed by computer to fuse metallic or non-metallic powders or grains together (Bikas et al., 2016). To begin the SLS process, the powder-feed piston delivers a fixed amount of powder onto the table and a roller will swipe across it to spread the powder evenly over the table surface. Compressed air is used to force the powder particles through a grounded or charged sieve on the sintering surface with the cross-sectional area of the design before the powder being levelled by a roller. After that, an infrared radiant heater will heat up the area with the powder layer to a temperature just below the melting point of the material, in order to minimize thermal distortion, part shrinkage and facilitate melt diffusion between layers (Bikas et al., 2016; Venuvinod & Ma, 2004).

A controllable moving laser beam then moves across the heated layer. The power of the beam is adjusted to bring the powder area to a temperature just sufficient for the powder particles to sinter or stick. Sintering may also occur through partial melting or softening of the powder particles, or coating on the powder particles. The sintered layer is allowed to cool down and the platform is lowered with a distance equals to the thickness of the sintered layer and a new powder layer is added. The process is repeated to build a 3D part. In SLS, no supports need to be built or removed, as sintered materials forms the part and unsintered material powder will remain in place to support the part structure (Bikas et al., 2016). Finally, the completed part is carefully removed from the powder mass by cutting. Excess unsintered powder is brushed off and the powder can be reused. The completed part can be polished and painted if required (Venuvinod & Ma, 2004). The process is illustrated in Figure 2.7.

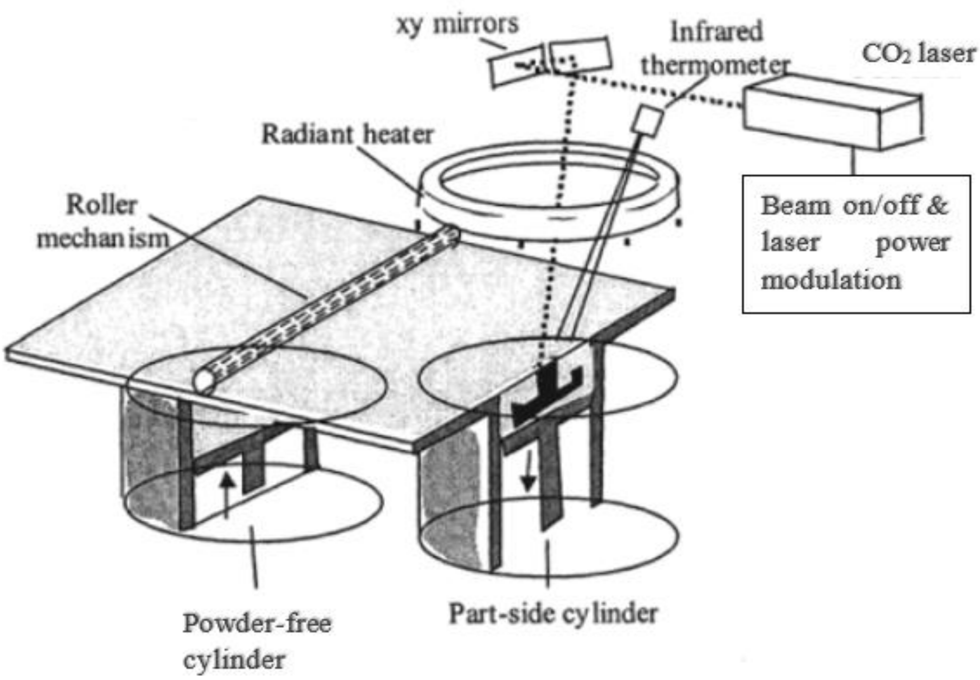

Figure 2.7: The SLS process (Venuvinod & Ma, 2004).

B. Electron Beam Melting

EBM is another powder-based process similar to SLS. This technique is used for incremental building metal parts layer-by-layer to reduce the need for tooling like moulds and jigs (Murr, 2015). Although this technique is relatively new to fabricate optimized and complex patterns, but it is growing rapidly. To fully melt the incremental metallic powder layer, high-energy electron laser beam powered by high voltage is employed. The typically voltage ranges from 30 to 60kV (Wong & Hernandez, 2012). As shown in Figure 2.8, the fabrication process begins with heating of the start plate to the melting point of the powder material, prior to first powder layer addition. The powder layer is then melted with electron beam and it forms the solid foundation of the part, or it forms a thin network-like support structure on which the real part is fabricated. A series of defocused beam at high power and speed is used to preheat the powder bed. Meanwhile, in the subsequent melting step, the power and scan speed are reduced.

After each selective melting phase, the build table is lowered with a one-layer-thickness distance, another powder is delivered by the powder hoppers and raked. These processes are repeated until a completed part is formed. Lastly, the part is cooled down under an increased helium pressure and it is covered with soft agglomerate powder or breakaway powder prior to removal from the building chamber. The breakaway powder is then removed by sandblasting. The whole fabrication process occurs in a high vacuum chamber to prevent oxidation. EBM can fabricate various type of pre-alloyed metals with full density functional and complex parts. For instances, Ni-based super alloys, low-expansion alloys (Invar), Co-based superalloys, etc (Galati & Iuliano, 2018).

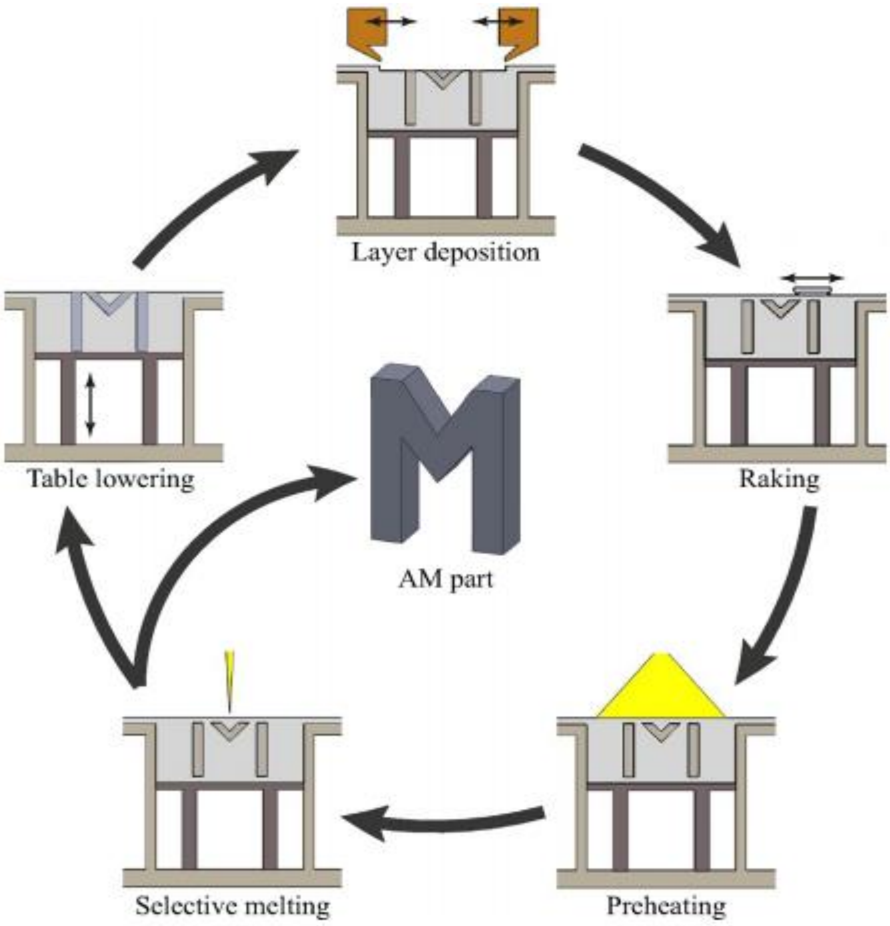

Figure 2.8: Schematic phases of EBM process (Galati & Iuliano, 2018).

C. Laser Engineered Net Shaping

LENS technology is also used for building metal parts from metallic powder. The metallic powder particles are directly injected by the specially designed powder delivery nozzle into the focused laser beam to build each layer. The laser head and powder injecting nozzle move together as an integral unit in x- and y- axes. A high-powered laser beam is employed to form a small molten pool on the base substrate material or the previous deposited layers. Metallic powders are delivered and distributed evenly around the circumference of the laser head, either by a pressurized carrier gas or naturally by gravity (Bikas et al., 2016). The metallic powder fed is consumed into the molten pool, resulting its height to grow away from the surface of substrate (Singh et al., 2017).

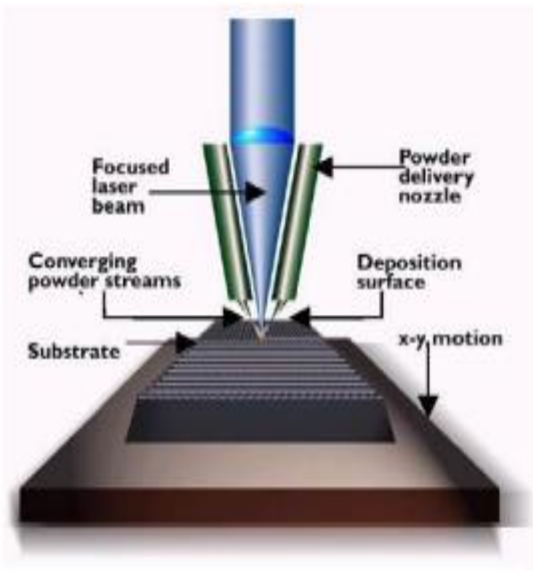

Figure 2.9: Schematic view of LENS process (Singh et al., 2017).

After melting of the powder layer, the substrate is moved beneath the laser beam or the head is moved up vertically with one-layer-thickness distance. Another thin cross-section layer is consecutively formed by repeating the powder injection and melting events until a 3D part with desired geometry is formed. The whole process is conducted under a controlled argon atmosphere where the oxygen levels are kept below 10 ppm (Singh et al., 2017). This technology can also be used to repair damaged parts as well as build substantially large and long parts. It does not need secondary firing processes.

However, some post-fabrication processes are still needed such as cutting from the build substrate, machining or polishing on the rough surface (Huang et al., 2013). Figure 2.9 shows the LENS process.

D. 3-Dimensional Printing

3DP process is totally different from SL process. A printing head is used to deposit a liquid binder onto the powder inside the build chamber. The printing head used is almost similar to those used in inkjet printers. Upon the deposition of liquid binder, the powder is bonded together and hardened. Once one cross-section layer of the part is completed, the platform will be lowered down with a distance equals to the thickness of the previous layer created. Normally there is a powder supply chamber beside the build chamber. A levelling roller will roll across from the powder supply chamber to the build chamber to replenish the powder layer. The roller also helps to compact and level the last bonded layer. The process is repeated to build up a 3D part. Finally, the excess powder is cleaned from the completed part and the part is typically impregnated with a sealant (Swift & Booker, 2013). The process is illustrated in Figure 2.10.

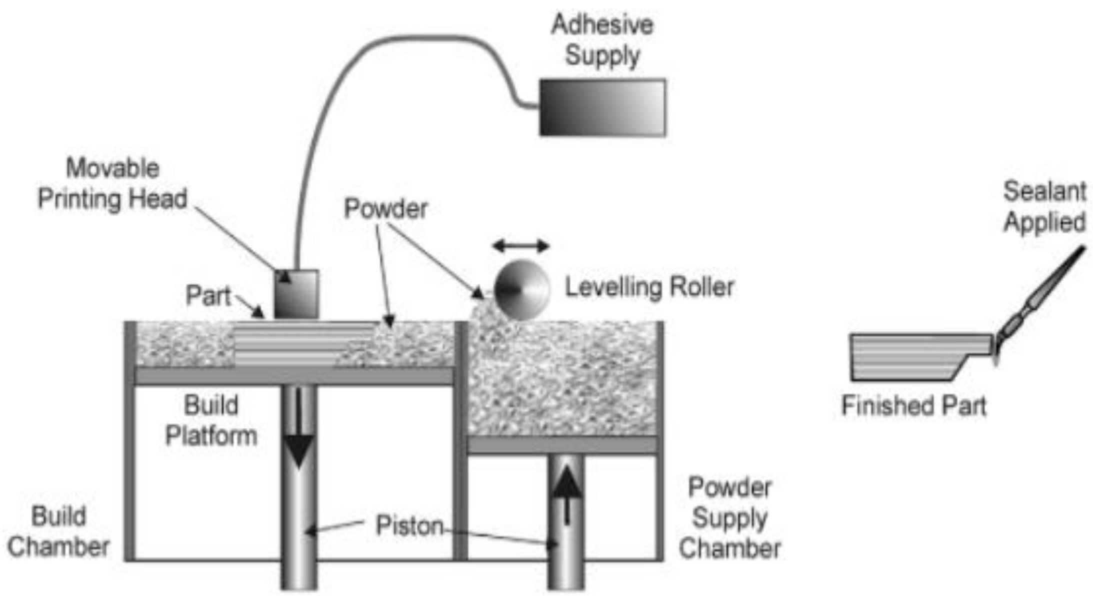

Figure 2.10: Illustration of 3DP process (Swift & Booker, 2013).

E. Prometal

Prometal is a metallic powder-based AM process to generate net-shape components by using specially formulated chemical binders to join loose metallic powder particles together (Godlinski & Veltl, 2005; Lembo, 2002). The process is illustrated in Figure 2.11. This technique is commonly used to build metal injection tools and dies. Before fabrication, the CAD file is firstly sliced into layers to generate a STL file. A thin distribution of powder is spread over the powder-bed surface to begin each layer fabrication. By employing a technology similar to inkjet printing, a liquid binder is spurt out in jets to selectively join the powder particles together (Wong & Hernandez, 2012). After one-layer formation, the powder-bed together with the part-in-progress is lowered by build pistons to a distance equals to the thickness of powder layer formed (typically 100 to 180 µm) for the second layer fabrication.

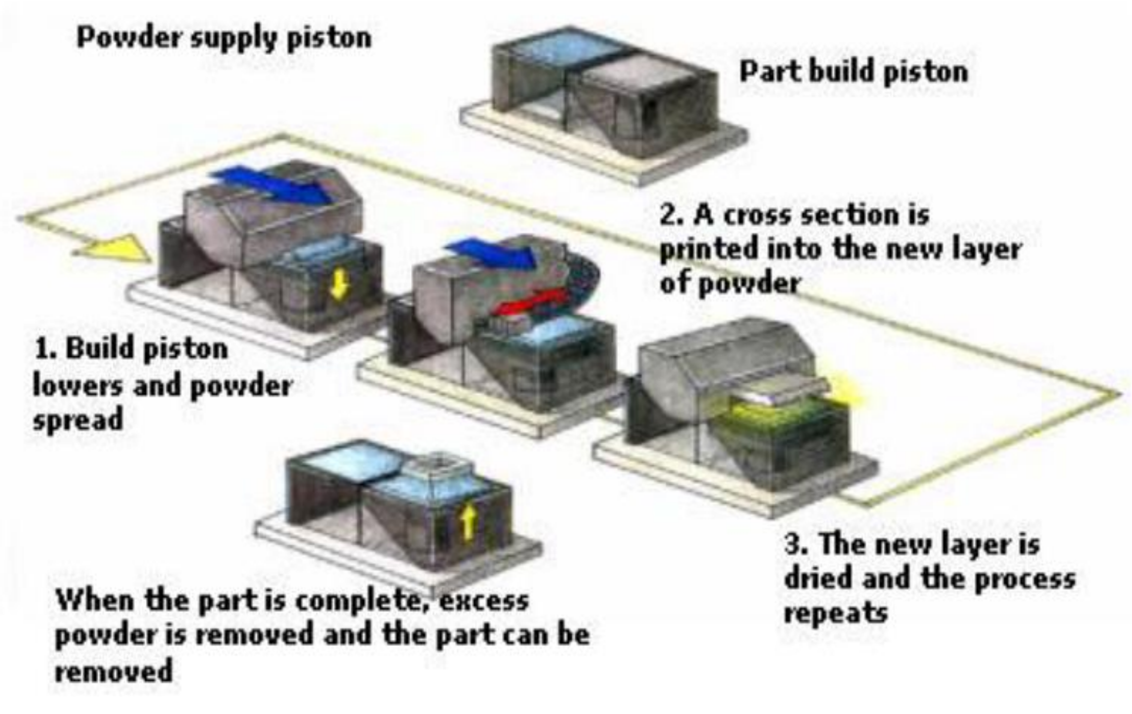

Figure 2.11: Illustration of Prometal process (Lembo, 2002).

The powder distribution by feed piston and binding processes are repeated for each layer until the part is completed. Upon completion, the whole part is heat-treated in furnace to remove organic binder and form a denser part, following by unbound powder removal and partial sintering without shrinkage at 350ºF for 24 hours to harden the binder fusing with the metal (Godlinski & Veltl, 2005). Finally, the sintered part is permeated or infiltrated with bronze powder by capillary forces and heating at 2000ºF to form alloy of 60% metal and 40% bronze. The infiltration can also fill up pores, confer full density and impart mechanical strength (Lembo, 2002).

2.4 Advantages of Additive Manufacturing

AM has enabled the manufacturing of parts or whole products without the need of traditional enabling mechanisms, such as labour. This technologies require skilled, partial-skilled or unskilled workers in the process, as the machine is automated, semi-automated, or manually handled (Eyers & Potter, 2017). There are five main benefits that AM has over the conventional manufacturing technology, which are cost, speed, quality, impact, and innovation or transformation. However, AM technology will not replace the traditional production technology but it will revolutionize many niche areas. The advantages of AM are summarized in Table 2.3.

Table 2.3: Summary on the advantages of AM (Attaran, 2017).

Area of Application	Advantages
Rapid Prototyping	• Short time to market with accelerating prototyping. • Low cost in product development. • Increase efficiency and competitive at innovation.
Production of Spare Parts	• Short repair times and labour cost. • Avoid expensive warehousing.
Small Volume Manufacturing	• Cost-efficient small batch production. • Avoid investment in tooling.
Customized Unique Items	• Fast production of exact and customized replacement parts on site. • Enable mass production at low cost. • Eliminate penalty on redesign.
Complexity of Work Pieces	• Complex work pieces at low cost.
Rapid Manufacturing	• Direct manufacturing the finished components. • Relatively cheap production in small amount.