An In-Depth Review on Direct Additive Manufacturing of Metals

Farooq I Azam* [1], Ahmad Majdi Abdul Rani[1], Khurram Altaf[1], T.V.V.L.N Rao[2], Haizum Aimi Zaharin[1]

1 Mechanical Engineering Department, Universiti Teknologi PETRONAS, Malaysia

2 Department of Mechanical-Mechatronics Engineering, The LNM Institute of Information Technology, India

Email: farooq.i_g03648@utp.edu.my

Abstract. Additive manufacturing (AM), also known as 3D Printing, is a revolutionary manufacturing technique which has been developing rapidly in the last 30 years. The evolution of this precision manufacturing process from rapid prototyping to ready-to-use parts has significantly alleviated manufacturing constraints and design freedom has been outstandingly widened. AM is a non-conventional manufacturing technique which utilizes a 3D CAD model data to build parts by adding one material layer at a time, rather than removing it and fulfills the demand for manufacturing parts with complex geometric shapes, great dimensional accuracy, and easy to assemble parts. Additive manufacturing of metals has become the area of extensive research, progressing towards the production of final products and replacing conventional manufacturing methods. This paper provides an insight to the available metal additive manufacturing technologies that can be used to produce end user products without using conventional manufacturing methods. The paper also includes the comparison of mechanical and physical properties of parts produced by AM with the parts manufactured using conventional processes.
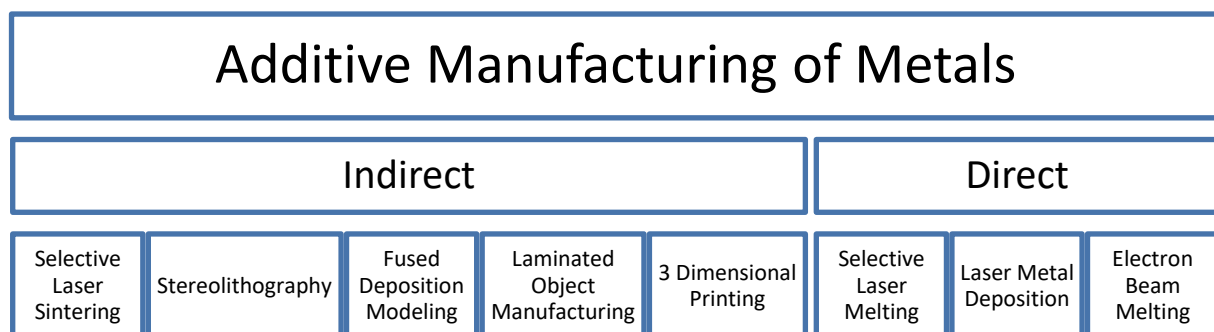
1. Introduction

Additive manufacturing has been around for decades and it is continuously evolving at an immense rate. This advancement in additive manufacturing techniques has attracted interest from both the academic community and the business world. AM is an umbrella which accommodates wide range of technologies and is known by many nick names such as Freeform Fabrication, Solid Freedom Fabrication, layer-Based Manufacturing, Rapid Prototyping, Additive Layered Manufacturing, Rapid Manufacturing, Additive Fabrication etc. [1-3]. The official definition of Additive Manufacturing (AM) is given by American Society for Testing and Materials (ASTM) F2792 as "process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [4]. This approach of AM to create products with increased efficiency, accuracy and reduced wastage makes it a more sustainable manufacturing process. Additive manufacturing stands out the most among other emerging manufacturing techniques and has the potential to replace conventional manufacturing process, allow for new products and change society as whole. However, this process is still in its early existence, but it has been showing signs of great future potential and has been enthusiastically embraced by a small number of early global adopters [5-7].
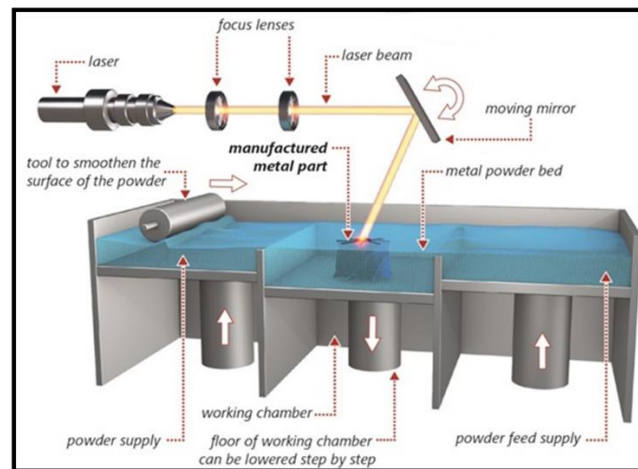
2. Metal Additive Manufacturing

Metal additive manufacturing consists of many different technologies, These technologies can be divided into two categories; the "direct" way is where the metal powder completely melts and solidifies to form the final part. In "indirect" way, a binder is used to join the particles of metal powder together and post processing is necessary to achieve desired density. Classification of AM processes for metals is shown in Figure 1. "Direct" methods for manufacturing metal parts using additive manufacturing including Selective Laser Melting (SLM), Laser Metal Deposition (LMD) and Electron Beam Melting (EBM). In all these technologies, metal powder fully melts and then solidifies to form the end product. All these technologies can produce denser parts compared to other AM technologies.

Additive Manufacturing of Metals							
Indirect					Direct		
Selective Laser Sintering	Stereolithography	Fused Deposition Modeling	Laminated Object Manufacturing	3 Dimensional Printing	Selective Laser Melting	Laser Metal Deposition	Electron Beam Melting

Figure 1. Classification of metal AM processes [8]

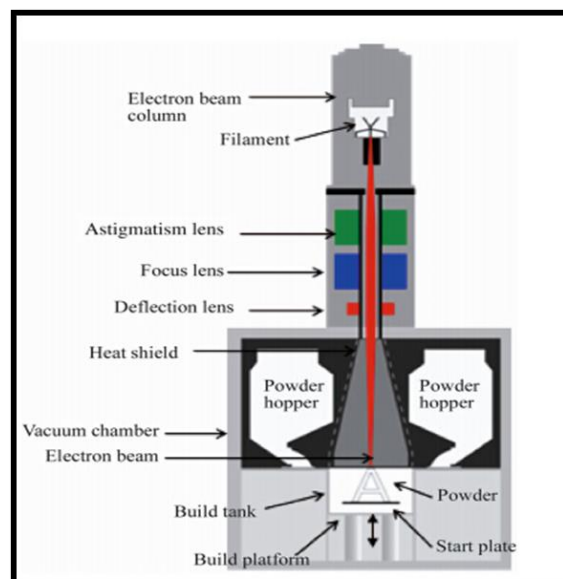### 2.1. Selective Laser Melting (SLM)

Selective Laser Melting is one of the industry's leading additive manufacturing technologies. It is precise and fast compared to other AM technologies. SLM is similar to SLS, but it goes a step further and rather than just sintering the powder particles to form the 3D part, SLM fully melts the powder particles to form the final part. SLM technology makes it possible to achieve approximately 100% density and a much stronger part, eliminating the need for postprocessing steps like infiltration, which are highly required in SLS or DMLS. SLM provides unlimited freedom of design and can produce highly complex shapes which can be impossible to manufacture using conventional manufacturing processes. [9] in his experimental study fabricated an impression block with conformal cooling channels for die casting using SLM. When compared to conventionally produced block, it was discovered that due to the conformal channels, the cooling rate increased and resulted in reduced need for spray cooling. It was also observed that the surface finish of casted parts improved and the cycle time was reduced [9]. As other AM processes, SLM process starts with a computerized 3D model which after sliced into layers, the information is fed to the SLM machine. A thin metal powder layer is spread across the metal build plate. Then the laser selectively scans the cross section on the material in x-y axes per the 3D data provided earlier. As the laser scans each layer, the powder particles are melted and consolidated into a homogenous part. Material which is not part of the model geometry is left unaffected and acts as a support structure. The build platform then lowers by a single layer thickness and the levelling blade sweeps across the build platform and covers it with another layer of powdered metal. The laser then scans the next layer and the process repeats building layer by layer until the part is completed [10-12]. The process is illustrated in Figure 2.

Figure 2. Selective Laser Melting (SLM) mechanism (Source: empa.ch)
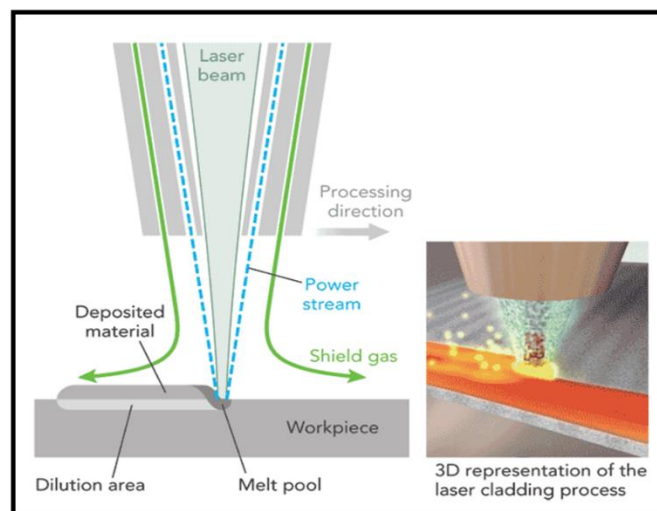
2.2. Electron Beam Melting (EBM)

Electron Beam melting is another additive manufacturing technology which forms 3D parts by full melting of powder particles. The key difference between laser based additive manufacturing technologies and EBM is the heat source. EBM, as the name suggests uses an electron beam instead of laser, which requires that the procedure is carried out under vacuum conditions to prevent dissipation of the electron beam. After being heated at a high temperature, the electrons are emitted from a filament. The beam of electrons is accelerated up to half the speed of light, controlled by two magnetic fields. One field acts as a magnetic lens and helps the beam to focus to desired diameter, whereas the second field deflects the focused beam to the build platform at a desired point. In EBM printer, as shown in Figure 3, the machine spreads a layer of powder material on the build platform. The electron beam melts the material powder per the data provided to it. The build platform is lowered and next layer of powder is spread. The beam traces the cross section of the next layer and melts the powder. The process repeats until the 3D part is built [13-14].

Figure 3. Electron Beam Melting (EBM) mechanism (Source: arcam.com)
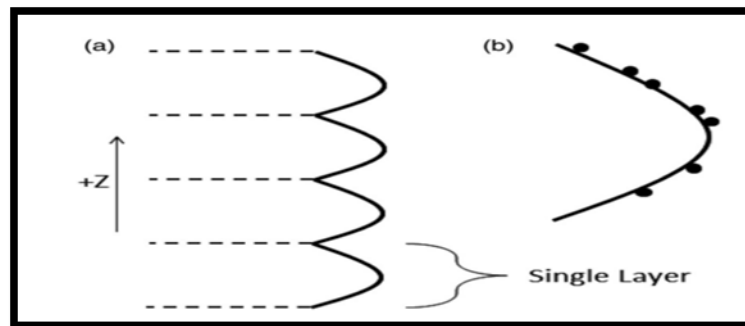
2.3. Laser Metal Deposition (LMD)

Laser metal deposition, also called as direct energy deposition and laser cladding, is a powder based additive manufacturing process, which is used to build 3D parts, repair metal components deemed nonrepairable by conventional methods or add features to existing parts. The process is very simple and it begins with a 3D model like other AM technologies. The model is divided into layers and the information is fed to the LMD machine. Molten pool is created by the laser beam on metallic substrate, then metal in powder form is applied through the nozzle into the melt pool by a meticulousness powder fed system as shown in Figure 4 below. The deposited powder then melts and is metallurgically bonded to the base material creating a weld bead. The process repeats building up layer by layer until the part is complete [15].

Figure 4. Laser Metal Deposition (LMD) mechanism (Source: industrial-lasers.com)

3. Physical Properties

When printing a metal part, the surface finish, mechanical properties and geometrical accuracies are the main concerns The size of the feedstock and the diameter of the heat source determine the minimum feature size. Smaller feature sizes lead to a smaller layer thickness which, as a result, give better resolution but at the cost of build rate/deposition rate. SLM has the minimum beam diameter and the smallest layer thickness compared to EBM and LMD. Thus, SLM has a higher resolution among the three. SLM has a minimum beam diameter of 50 µm compared to EBM's 140 minimum beam diameter. Compared to LMD's minimum layer thickness of 100 µm, SLM has a minimum layer thickness of 20 µm. Minimum feature size is also advantageous for SLM and EBM for printing metal mesh structures. SLM and EBM can also be utilized to build complex geometries with overhangs whereas with LMD, support structure may be required (5 axes can be utilized to eliminate support structures) [16]. Two factors contribute to surface roughness of metal; Layer roughness and actual roughness [17], as shown in Figure 5..

Figure 5. Factors for surface roughness in AM (a) Layer roughness (b) Actual roughness [17]

Layer roughness effect can be reduced by decreasing layer thickness, but doing so would result in longer build time, whereas actual roughness of metal surface depends on the machine used, build direction and process parameters. As 3D parts in AM are built layer by layer, reducing the layer thickness would result in higher number of layers. Thus, EBM and LMD with a larger layer thickness have a higher build rate compared to SLM. This higher build rate comes at the expense of geometrical accuracy. Larger layer thickness comes in the way of achieving near net shape part and machining is required to accomplish final geometry and details.

4. Mechanical Properties
The yield strength, ultimate Tensile Strength, % elongation and hardness from published data have been summarized in Table 1. The data from EBM, SLM and LMD is compared with the values obtained from conventionally cast and wrought test specimens. EBM processed specimens show superior mechanical properties compared to cast specimens, but are almost equivalent when compared to wrought specimens. SLM on the other hand has superior UTS and Ys compared to EBM, wrought and cast parts. However, it should be noted that the ductility is lower compared to them. LMD like SLM has higher UTS and Ys compared to the EBM, wrought and cast samples but a lower ductility. When comparing SLM and LMD, SLM shows either superior or equivalent mechanical properties. [18] in his study demonstrated that SLM specimen of Ti6Al4V ELI exhibited a superior fatigue limit (550 MPa), whereas EBM samples of Ti6Al4V ELI showed an inferior fatigue limit (340 MPa).

Process	Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Hardness (HV)	Reference
Wrought	Ti6Al4V ELI	860	931	14	327	[19]
	Ti6Al4V	860	930	10	-	[20]
Cast	Ti6Al4V ELI	734	851	4.4	333	[19]
	Ti6Al4V	758	860	8	-	[20]
EBM	Ti6Al4V ELI	930	970	16	318	[21]
		869	928	9.9	327	[18]
	Ti6Al4V	950	1020	14	327	[20]
		883.7 - 938.5	993.9 – 1029.1	13.6 – 13.2	-	[22]
SLM	Ti6Al4V ELI	1143	1219	4.89	403	[18]
		996 ± 10	1110 ± 13	7 ± 4	399 ± 4	[23]
	Ti6Al4V	990 ±5	1,095 ± 10	8.1 ± 0.3	-	[24]
		1116 ± 61	1286 ± 57	8 ± 2	384 ± 5	[25]
LMD	Ti6Al4V	1062	1157	6.2	-	[26]
		976 ± 24	1099 ± 2	4·9 ± 0·1	360 ± 10	[27]
		1025 - 1085	1138 - 1168	3.4 – 3.7	390 ± 2	[28]
		973	1077	11	-	[29]

Table 1. Comparison of Mechanical Properties of Different AM Technologies

5. Conclusion

As the interest of different industries is growing in AM, more and more AM equipments are available in the market. Different AM technologies serve different purposes from rapid prototyping of novel products to rapid manufacturing of end products. Many different AM technologies are available with numerous different parameters which affect the final product.[30] estimated that there are approximately 130 parameters that can impact the SLM process, of which, 13 are critical to the quality characteristics of the final manufactured parts. In SLM, EBM and LMD many different process parameters affect the final product and the mechanical properties of these processes are either equivalent or higher compared to conventional manufacturing techniques (wrought, cast, etc.). Regardless of the processes, what matters more is the suitability of a final product for a specific application. For instance, SLM can be chosen for an application requiring superior part strength, whereas EBM can be selected if the application requirement is a moderate strength ductile part. Therefore, selection of a specific process, may it be LMD, EBM or SLM, largely depends on the requirements for end-use. Thus, proper understanding of the final product application is necessary for choosing the right AM process.

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