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*Review Article*

# A Review on Additive Layer Manufacturing

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***Abstract***

*Additive layer manufacturing (ALM) is a process for joining materials to build objects in successive layers under computer control using data from 3D model. It is an opposite of subtractive manufacturing in which material removal is required to reach the desired shape. ALM has better capabilities than the original 3D printing that used mainly for rapid prototyping because it makes the production more efficient if it is used in advanced applications such as creating highly customized products, producing small volume of serial components and visualizing tool in design, the future applications may concern human organs creation, clothes manufacturing and food confection. The aim of this paper is to present a review about ALM showing its application, processes and quality issues focusing on fused deposition modelling as it is the most traditional ALM process.*

***Keywords:*** *Additive Layer Manufacturing, 3D Printing, Fused Deposition Modelling.*

## 1. Introduction

Additive layer manufacturing (ALM) is a process for joining materials to build objects in successive layers under computer control using data from 3D model (Farinia Group). It is an opposite of subtractive manufacturing in which material removal is required to reach the desired shape. ALM includes other terms such as 3D printing, rapid prototyping, digital manufacturing and layered manufacturing, it is commonly preferred to use additive layer manufacturing term in industrial context rather than 3D printing since not all processes look like printing, but all of them are additive. However, ALM has better capabilities than the original 3D printing that used mainly for rapid prototyping because it makes the production more efficient if it is used in advanced applications such as creating highly customized products, producing small volume of serial components and visualizing tool in design, the future applications may concern human organs creation, clothes manufacturing and food confection.

O. Abdulhameed (Abdulhameed *et al.*, 2019) stated that there are certainly many advantages associated with additive layer manufacturing processes such as ease of using them, flexibility of the design, customization of the product, capability to print highly complex structure. However, there are some challenges and drawbacks the need further investigation and improvement.

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The major disadvantages are void formation between sequential layer due to reduced binding, the appearance of stair stepping effect in the fabricated part, the variation in microstructure and mechanical proprieties, the small build volume that lead to scaling down large parts or cutting them to subparts consuming effort and long time, complying with safety standards for fabricated food and medical devices and finally fabricating and producing parts that can used for crime purposes such as drugs and weapons as it has the ability to deal with complex structures as mentioned previously.

## 2. Additive Manufacturing Applications

The typical applications for ALM are prototyping during development phase of the product, producing parts in pilot series production or short series where costs related to casting or injection molding are high and producing parts with complex geometry which cannot be done by other manufacturing means (Metal AM). This feature is the outstanding advantage of ALM and gives it the edge among other processes, in addition to allowing the integration of additional functions and new technical parts as can be seen in the parts with 7 repeating internal patterns. ALM is capable for combining the complex internal structure with outer geometric as can be done in manufacturing the frame of the bike. Furthermore, O. Abdulhameed (Abdulhameed *et al.*, 2019) presented some applications in the context of aerospace and automotive industry such as producing and fabricating metal parts directly using titanium material, which is suitable for aircrafts, using this technology increased the productivity of the sector as the lead time was declined by 30% - 70%, non-recurring costs of the fabricated product was reduced by 45% and 30% - 35% abatement in manufacturing cost for parts with low volume.

## 3. Additive Manufacturing Processes

The processes in ALM always start with CAD model that must be converted to STL file and then exported to additive layer manufacturing machine. This machine has many different processes along with its techniques and materials as shown in the following table:

**Table.1** Additive Manufacturing Processes (Farinia Group)

| Process | Techniques | Materials |
|---|---|---|
| Powder bed fusion | Direct metal laser sintering (DMLS), selective laser sintering, selective laser melting and electron beam melting | Polymers, metals: miraging steel, stainless steel 316L, 15-5PH, nickel-based superalloys: Inconel 718, Inconel 625, Hastelloy X, titanium TA6V, chrome-cobalt, aluminum AISi10mg |
| Material extrusion | Fused deposition modelling (FDM) | Thermoplastic filament |
| Material deposition | Material jetting and binder jetting | Photopolymers and wax-like materials |
| Sheet lamination | Laminated object manufacturing (LOM), paper lamination technology (PLT), ultrasonic additive manufacturing (UAM) | Adhesive-coated papers, metal tapes and foils, plastic sheet material |
| Vat photopolymerization | Stereolithography (SLA), digital light processing (DLP) | Light curable resin |
| Directed energy deposition | Laser engineered lens shaping (LENS), direct metal deposition (DMD), blown powder, laser cladding | Metals such as nickel-based alloys and aluminum |

## 4. Fused Deposition Modelling

This section presents a brief review of FDM process showing its way of working, advantages, limitations and parameters.

### *4.1 Definition and Way of Working*

The most typical ALM process is FDM in which computer aided design (CAD) model is used to create physical object in layer by layer deposition as stated by S.H. Masood (Masood, 2014), he said that it is one the most widely applied ALM processes because it is easy and safe to use, its cost is low and has the ability to process thermoplastic filament production. In addition, he mentioned three machines that can be used to build the object, the first one uPrint 3D printers which is smaller, has lower cost and easier to transfer ideas to physical objects, the second one is dimensions 3D printers that offer higher performance and has the flexibility to build large objects and the last machine is fortus 3D production systems that aimed to produce the parts more accurately. F. Liang (Liang *et al.*, 2018) showed the four stages of FDM process starting from modelling, layered slice, printing and post processing as shown in the following:


**Fig.1** FDM Flow Chart (Liang *et al.*, 2018)

Furthermore, they presented the structure of FDM printing system in terms of control system and mechanical structure:

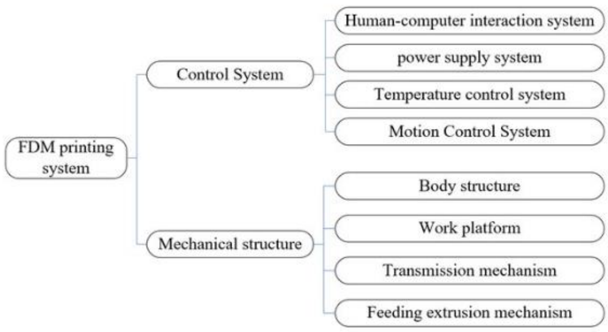


**Fig.2** The Structure of FDM Printing System (Liang *et al.*, 2018)

### *4.2 Advantages and Limitations*

S.H. Masood (Masood, 2014) also discussed the advantages and limitations of using FDM process, the advantages are ease of use, safety, no waste for material, variety of building styles and engineering polymers, can be used with new materials, material can be changed easily, and removal support can be done easily as well. However, there are some limitations such as limited accuracy, slow building speed, meeting feedstock filament requirements and mechanical proprieties are not the same in all directions.

### *4.3 Parameters*

S.H. Masood (Masood, 2014) mentioned number of FDM process parameters that enable the user to control the structure, size and shape of the fabricated parts. The main process parameters include layer thickness which is the distance between successive layers in z direction or can be called slice height where that model is sliced to build the parts, other control variables are model tip size which is the diameter of the model, model build temperature which is the temperature of the heating element, raster width which is the width of beads, raster angle with respect to x axis, air gap with its three types (raster to raster, part sparse fill and perimeter to raster), fill style of the part showing the tool path and finally the interior style of the parts which determine if each layer needs to be filled with specified air gap or not.

Furthermore, X. Zhou & S. J. Hsieh, (Zhou & Hsieh, 2017) investigated the effect of FDM process parameters on temperature distribution and thermal history, four parameters we selected: platform temperature, nozzle temperature, printing speed and layer thickness. In addition, they developed an experimental model to measure the temperature of deposited layer and its corresponding thermal response through infrared thermography imaging. They constructed a three-dimensional model to simulate FDM process, thermal response acquired from the experimental model was used to validate the model. It is found that numerical model is more reliable in representing road-to-road bonding mechanics and bead spreading during fabrication. However, both models found that the setting that yield longest diffusion time is 70 oC platform temperature, 220 oC nozzle temperature, 40 mm/s printing speed and 0.25 mm layer thickness.

*4.4 Gaps and Open Issues*

S. Vyavahare (Vyavahare *et al*., 2020) discussed the current gaps and open issues that need to be addressed and fulfilled in the future, they started with gap related to design for manufacture suggesting for future researcher to frame guidelines for FDM parts design. Due to phase transformation, fast cooling and exhaustive energy, parts fabricated by FDM process deviated from the desired geometry so that post-production finishing techniques is required to make needed compensation. Numerical modelling is another point for potential improvement by performing a simulation model using layer-wise material proprieties, this aids in designing FDM parts. They also mentioned the potential improvement in terms of environmental factors by finding the optimal values of temperature and humidity for FDM parts fabrication. The authors emphasized on the opportunities for future researcher to optimize the process for FDM feedstock material other than poly-lactic acid and acrylonitrile butadiene styrene, in addition to optimize the process parameters for thermal and chemical proprieties, maximize the material utilization by perceiving the values of process parameters automatically using material and loading data and undertake a research about setting the dynamic process parameter. After finishing the production, nondestructive evaluation is another gap area that require in situ monitoring for the process to get component free from defects. In addition, the researcher may study the effect of sterilization and metal coating on the fabricated parts as one of the post-production finishing techniques for further improvement.

## 5. Quality Improvement in Additive Manufacturing

Additive layer manufacturing products need advanced quality control process to achieve the desired reliability, so it is valuable to review quality related research in ALM context by focusing on quality issues, considerations that need development and optimization and future directions toward improving the quality for ALM products. (Kim *et al*., 2018) presented the research progress about quality control for each of the seven ALM technology photopolymer vat processes, material jetting processes, binder jetting processes, extrusion-based processes, powder bed fusion processes, directed energy deposition processes and sheet lamination processes. The review showed the new trend of using camera and sensors to acquire real time data for quality monitoring purposes in addition to showing advanced data analytics and predictive algorithms to optimize the process parameters.

*5.1 Photopolymer vat Processes*

(Kim *et al*., 2018) mentioned that there are tools that can be used to provide accurate custom-design data such as computed tomography (CT) and magnetic resonance imaging (MRI), they help to evaluate dimensional accuracy by comparing the designed model with scanned data. In addition, they said that Stereolithography (SL) can be influenced by the orientation for the fabricated design, the deposition orientation has an effect on three significant parameters surface quality, support structure and build time, so algorithms were developed to determine the optimal fabrication orientation. Furthermore, a new adaptive slicing algorithm were developed in the design stage to improve the build performance by quantifying the tradeoffs among geometry tolerances, surface finish and build time. The dimensional and geometric proprieties can be predicted by adjusting the process parameters in the algorithm in order to reach to the desired design requirements.

*5.2 Material Jetting Processes*

(Tourloukis *et al*., 2015) predicted the quality of 3D inkjet printed electronic products using neural network algorithm. They used the past values of layer thickness as an input and defined them at each discrete time step, the output of the network is the next state values of resistivity. The authors used one-step ahead prediction where the network has the capability to remove delay states and make one-step ahead prediction after finishing the training. They used 18 observations to predict the 19th value of the resistivity using two and four delay states, the model failed to predict the 3rd and 9th values with error values of 11.7% and 29.59% respectively while the model was more accurate in the four delay states with error range between 0.28% and 10.44%.

The other type of prediction is using multi-step ahead prediction where removing a delay state is not needed and the network model has the capability to make multi-step ahead prediction, the model was accurate in the first four observations and the error was increasing in the next 14 observations reaching to error percentage of 50.13%.

*5.3 Binder Jetting Processes*

(Kim *et al*., 2018) showed that there are some researchers used mathematical analysis to improve the quality of the process. They used design of experiments technique (DOE) to investigate the significant factors affecting the dimensional accuracy, porosity and compressive strength, they found that printing orientation and delay time of applying new layer have the significant influence. In addition, other researchers used analysis of variance (ANOVA) to find the parameters that have significant effect on product quality, they found that layer thickness, binder saturation and building orientation have the significant contribution.

*5.4 Extrusion-based Processes*

Dimensional accuracy is the most common issue in fused deposition modelling process which is one of the most popular extrusion-based processes (Kim *et al*., 2018), the authors showed a study to predict the dimensional accuracy using artificial neural network, the model provided error range between 0 - 3.5%. They concluded that an increase in layer thickness led to decrease in number of required layers which leads ultimately to minimize the distortion of the fused deposition modelling products.

*5.5 Powder Bed Fusion Processes*

(Kim *et al*., 2018) mentioned that most of the powder bed fusion processes melt powder-based material using high source of thermal energy, it might be partial melting as happens in selective laser sintering, full melting in selective laser melting or using electron beam melting. Detecting porosities has a significant contribution toward improving the quality of products. (Kim *et al*., 2018) showed a study that developed a method for continuous data capturing using infrared (IR) camera to detect porosities inside materials. In addition, they showed other study that developed automatic feedback control system that stops printing process at certain porosity level, they used IR camera as well to capture images and used image processing technique to optimize the process parameters.

*5.6 Directed Energy Deposition Processes*

Researchers in this kind of processes conducted studies to monitor the height of the layer using charged-coupled device (CCD) camera and artificial neural network algorithms. (Kim *et al*., 2018) presented a study that used three CCD cameras positioned at 120 degree around the nozzle, they measured the clad height using hybrid novel algorithm that consists of image-based tracking protocol and recurrent neural network.

*5.7 Sheet lamination Processes*

Predicting the surface roughness is a key point toward improving the product quality, (Kim *et al*., 2018) showed a study that predicted sloped surface roughness considering surface angle and layer thickness as they are the significant parameters affecting the surface roughness.

In general, (Kim *et al*., 2018) proposed a classification for additive manufacturing cycle starting with modelling that includes pre-quality control, preparing material, optimizing design parameters and developing analytical modelling and predictive algorithms. The second stage is printing with in process quality control, optimizing printing parameters and real-time monitoring and printing control with closed feedback loop. The third one is post-processing that includes correction methods for detected defects and post quality control. The final stage is evaluation process externally and internally using 3D scanning, machine vision and non-destructive and destructive testing. To achieve agile ALM processes from modelling to evaluation stage, it is important to address these potential issues in the future:

- Predicting optimal printing parameters and mechanical properties using analytical modelling rather than iterative tedious methods.
- Developing robust real-time monitoring model with closed feedback loop control for defects detection during building process rather than waiting till the end of the process, it integrates data collection, image processing, machine vision and closed feedback loop.
- Achieving cyber quality control with remote correction to enable massive and customized ALM productions with less cost and time.

## Conclusion

Additive layer manufacturing (ALM) is a process for joining materials to build objects in successive layers under computer control using data from 3D model. It is an opposite of subtractive manufacturing in which material removal is required to reach the desired shape. ALM has better capabilities than the original 3D printing that used mainly for rapid prototyping because it makes the production more efficient if it is used in advanced applications such as creating highly customized products, producing small volume of serial components and visualizing tool in design, the future applications may concern human organs creation, clothes manufacturing and food confection. This paper presented a review about ALM showing its application, processes and quality issues focusing on fused deposition modelling as it is the most traditional ALM process.

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