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Additive Manufacturing Methods: A Brief Overview

Amir Dehghanghadikolaei[1], Navid Namdari[2], Behrouz Mohammadian[2], Behzad Fotovvati[3]

[1]School of Mechanical, Industrial and Manufacturing Engineering, Oregon State University
[2]Mechanical, Industrial and Manufacturing Engineering Department, The University of Toledo
[3]Department of Mechanical Engineering, The University of Memphis

Abstract Additive manufacturing (AM) processes are a types of methods that fabricate parts by adding elements and segments of a designed feedstock material. These materials can range from polymeric and plastic to metallic and ceramic. Based on different needs, a specific method can be implemented. Different methods utilize different deposition techniques. Some of them melt the materials and some change the materials into semisolid form. Different heating sources such as laser and resistance heaters van be used to change material states. The most common processes are Stereolithography (SLA), Liquid thermal polymerization (LTP), Fused deposition modeling (FDM), Ballistic particle manufacturing (BPM), Selective laser melting (SLM), Laser engineered net shaping (LENS) and Binder jet printing (BJP).

Keywords Additive manufacturing, Stereolithography, Ballistic particle manufacturing, Selective laser melting

Introduction

Additive Manufacturing (AM) processes, which are also known as Rapid Prototyping (RP), refer to an evolutionary type of fabrication that utilize a 3D CAD file and slice it to different thicknesses. A computer uses the sliced files as geometry of each layer and orders the fabrication setup to deposit a layer regarding that geometry [1, 2]. The layer-by-layer deposition continues to the last layer in order to fabricate a complete 3D component. There are various deposition methods that are working on different basis. However, these processes are similar in the thermal, chemical and mechanical ways they fabricate parts. The most common processes are Stereolithography (SLA), Liquid Polymerization (LP), Fused Deposition Modelling (FDM), Ballistic Particle Manufacturing (BPM), Selective Laser Melting (SLM), Laser-Engineered Net-Shaping (LENS) and Binder Jet Printing (BJP) [3-8]. Although many benefits come out of AM processes, many of them are yet available in lab scales and they are not ready for commercial uses. AM processes can be categorized to solid, liquid and powder-based types that as comes from their names, they are working with solid, liquid and powder feedstock. Some of the benefits of AM processes can be summarized as: i) no need of tooling design, ii) no need for separate machines and iii) less waste of materials and final cost.

AM processes fabricate parts in layer-by-layer format which is completely different than conventional ones. As a result, these processes have to undergo a deep investigation regarding their mechanical, thermal and chemical properties in dynamic and static conditions [9-14]. As an instance, Ibrahim *et al.* [15], have investigated effect of AM on corrosion properties of AM-fabricated NiTi shape memory alloys that have wide application in biomedical fields. Although it has been mentioned that AM processes are able to fabricate parts in one step, there might be needs to have some post-processing after fabrications. It is known that in metallic AM-fabricated parts, surface roughness is not very desired. Abrasive finishing processes such as magneto-rheological abrasive flow finishing (MRAFF) as proposed by Dehghanghadikolaei *et al.* [16], is a reliable options for post-processing these parts. However, in most of the cases of AM, there is no need to perform machining processes (such as high-speed machining [17]) in order to have the final geometry and precision. As said above, AM processes are layer-by-layer fabrication and there is a possibility of delamination or increase in corrosion in metallic parts. A good solution to this problem is implementing coatings on surface. In research by Dehghan *et al.* [18] and Dehghanghadikolaei [19], sol-gel process is introduced as a reliable coating and sealant process.

Stereo lithography (SLA)

Stereo lithography (SLA) is one of the most common types of AM. in this process, the feedstock are in liquid form and after impact of a ray of light (laser, UV, etc.), they solidify and form each layer. This process is called curing step of SLA. As the materials are solidified by light curing, the thickness of each layer cannot pass a specific value that depends on feedstock material properties and intensity of light emitted. Also, reflectivity of materials plays an important role in fabrication process [20]. Similar to the concept of all AM processes, after solidification of a layer, the ram of sample holder descends and a next layer is deposited and solidified, consecutively. However, based on complexity of the geometry, there might be some modifications and considerations needed to have a solid 3D component. These features are known as supports, overhangs and undercuts [21]. As mentioned before, the steps of SLA AM process are: a CAD model is used as a reference and a software slices the model. A processing unit obtains the slices and send them to a CNC machine equipped with deposition head. Each layer solidifies and at the final step a 3D component is fabricated. Figure 1 represents a schematic SLA setup. Benefits of this process are that there is flexibility in materials selection and a high accuracy can be achieved but all materials cannot be used and the fabricated parts must undergo a curing process after completion [22].

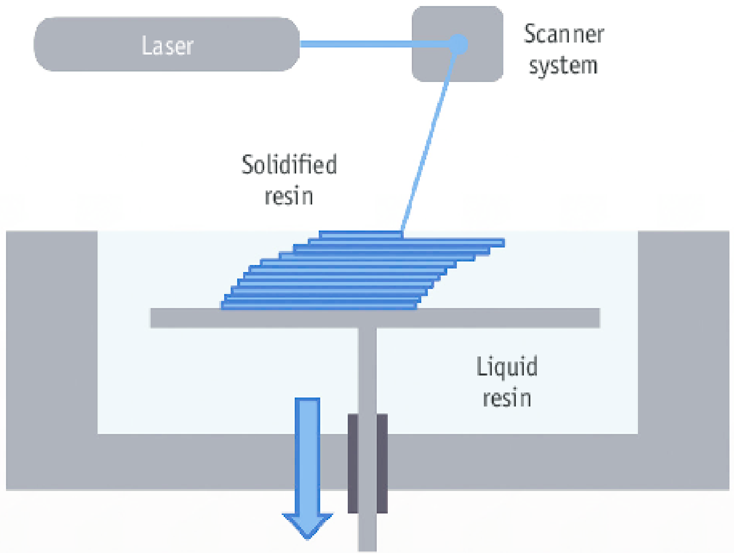

Figure 1: Schematic Stereolithography setup [23]

Liquid thermal polymerization (LTP)

Another interesting technique of AM is called liquid thermal polymerization (LTP) that is able to form layers of thermoset materials instead of photo-curable ones in SLA[24]. In this process some jetting heads feed the materials in liquid form on the surface. The computer control tells the machine where to deposit the liquid polymer droplets in order to form a deposition layer. On the other side, another head is in charge of addition of adhesive materials to the droplets on the surface. After heat dissipation of the deposited materials, they become solid layers of a desired composition [25]. The thickness is not uniform as it is difficult to control droplet geometries. The other step is to use a milling machine in order to make a uniform thickness throughout the surface and prepare the materials for next layers of deposition [26]. This sequence continues until the process is finished. As the surface is machined after each step of deposition, the texture and surface quality are very good but these extra steps increase the time of fabrication process. However, as this machine is in an office size and portable versions, it could be a very reliable option for desktop material printing. Figure 2 represents a schematic LTP process that utilizes laser.

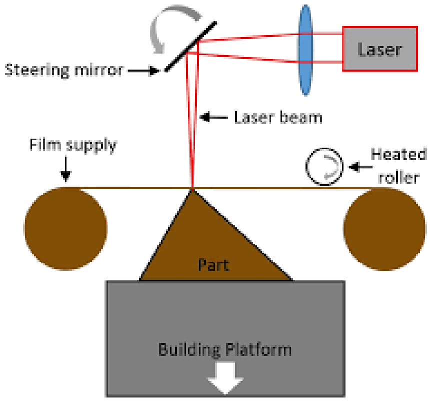

Figure 2: Schematic representation of LTP setup [7]

Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) is a type of additive manufacturing of polymers that does not utilize laser. This setup is equipped with a computer-controlled nozzle head that deposits semisolid materials on a surface on order to form a layer. This process is widely used in deposition of hard polymers as they are in semisolid form prior to deposition [27]. The deposition materials exit the nozzle head in a filament mode with variable diameters and geometries depending on nozzle head condition. The fabrication takes place in a layer-by-layer mode again. Similar to LTP, after deposition of each layer, a milling head cuts the surface to adjust surface finish and thickness of the layers [28]. In order to facilitate material deposition, the process of FDM takes place in a temperature close to melting point of the polymeric materials. In addition, a second nozzle can be added to the setup that are able to deposit secondary materials in order to have a composite and modify properties of the fabricated component [29]. A benefit of using this process is obtaining a finished part at the end without needs for post-processing and machining. Besides, it can be used in office scale, as well.Materials such as acrylonitrile butadiene styrene (ABS), medical grade ABS and E20 can be used in FDM. As it is known, ABS is a tough polymer with high wear resistance. However, there are some modifications in feedstock materials to enhance properties of FDM parts. On small pieces, there is no need of supports while like other AM processes, when the parts are complicated, a set of supports must be assigned to the design. Although this process offers many benefits, it is unable to use a wide range of materials and provide a high surface quality and geometrical accuracy [30]. Figure 3 shows a schematic FDM process setup.

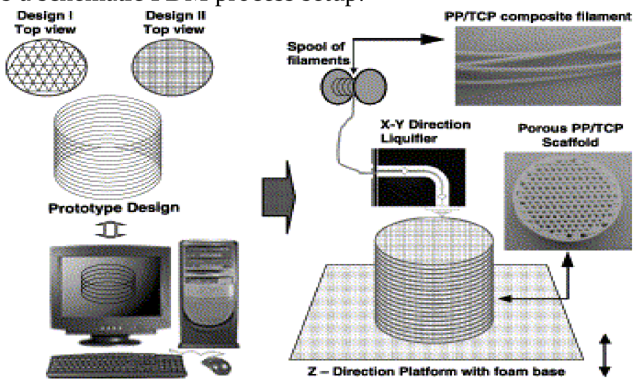

Figure 3: Schematic overview of FDM process [27]

Ballistic Particle Manufacturing (BPM)

Another interesting category of AM processes is known as ballistic particle manufacturing (BPM). In order to have a continuous stream of materials exiting nozzle, a set of piezoelectric are designed and based on pressure excite the nozzle sensors and ensure that there is a flow of materials. However, the materials can be applied as droplets [31]. When the deposition material faces the cold substrate, the semisolid form changes to solid quickly and to some extent the material is welded to the previous layers. On the other side, an electrical field is utilized to guide the droplets or flow of materials into the desired locations and form the needed design and geometry [32]. The process resamples ink-jetting but with the difference that it is a 3D process and it is controlled by a computer processing unit. Similar to other processes, in complex geometries there is need for support design. However, the supports can be made of a specific material that can be dissolved in solvents. With this feature, there is no limitation in removing support pillars from different parts of a complicated design [33]. In addition, BPM can be conducted in protected atmosphere that releases high geometrical accuracy and surface quality with no further need to post-process the fabricated parts. also, it has been mentioned in literature that the density of the parts are high enough to have a performance close to the conventionally-fabricated parts [34]. Figure 4 illustrates an overview of BPM.

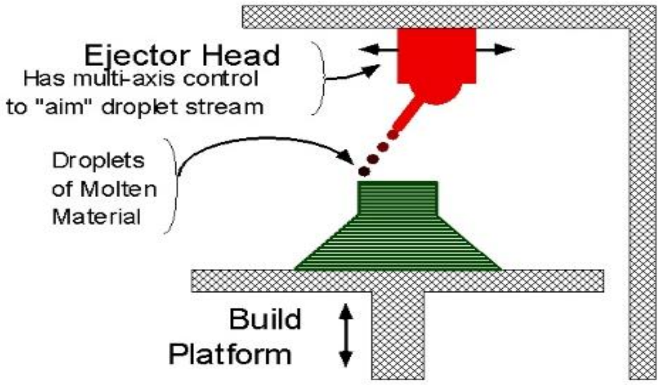

Figure 4: A schematic view of BPM [35]

Selective Laser Sintering (SLM)

Selective laser melting (SLM) is a solid process of AM of metals. Mostly, a more advanced controlling setup is required relative to the polymer processing methods. In this process, a bed pf selected material powder feeds the chamber of fabrication. A roller, also known as coater, feeds the metal powder materials into the place of fabrication [36]. The same as other AM processes, a computer design file will provide the geometry of each layer and an integrated laser head will get the G-codes and move on the designated paths. After each pass of laser, the materials that had interaction with laser will melt and the rest of powder particles remain untouched [37]. These particles can be reused until they are not under thermal effects of laser beam. This process is mostly done under controlled atmosphere of vacuum or inert gases at air pressure. After layer-by-layer manufacturing the parts, a final component with a density over 99% can be achieved that offers superior mechanical and chemical properties [38]. The most common reaction in melt pools of SLM is fusing the particles together and bond them mechanically and chemically. From advantages of this process, high flexibility and process speed can be named. However, the process is flexible in materials selection and it can give high accuracy of the final parts after the component is fabricated [39]. All being said, SLM is a process that can do process on different materials such as engineering plastics, polymers, and ceramic and metal oxide materials and from this point of it has the high power of laser in charge of melting powders. Also, among all AM processes, SLM is the fastest one and it is able to fabricate multiple parts in one round [40]. Figure 5 represents a schematic overview of SLM process.

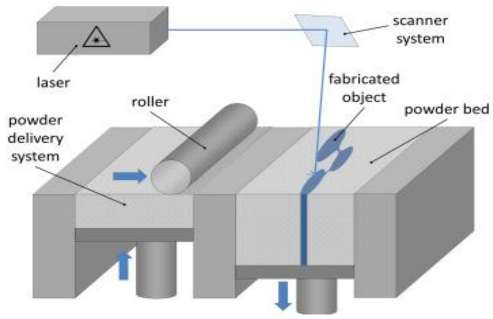

Figure 5: Schematic view of SLM [41]

Laser engineered net shaping (LENS)

Laser engineered net shaping (LENS) is a type of AM processes that is mostly used for metallic materials. This method is a close match to SLM with slight differences [42]. In this technique, a computer-controlled head moves above a surface and the powder materials are fed into nozzles that are coaxial with the laser head. A pressure of air or inert gases propel the feedstock to the tip of the laser and after reaching to the deposition surface, the materials are melted by a focused laser spot with adjustable energy densities [43]. Similar to SLM, the density of the parts fabricated by LENS are over 99% and they have a reliable performance in mechanical and chemical environments [44]. This process is able to fabricate complex geometries and again similar to other AM processes, for some designs, it needs supports and overhangs to reduce part distortion during the process. The flowing feedstock on the other hand, can facilitate cooling of the deposited materials and enhance density and integrity of the structure. Although this process is a powder-based one, it has been reported in literature that rods, wires and larger particles can be used for feedstock materials. LENS is able to fabricate tough and difficult-to-cut materials such as in conel, NiTi, stainless steel and some other soft metals such as aluminum and copper. As it is known, AL and Cu have high reflectivity and make difficulties during laser processing but in this method, this negative effect is minimized or in some cases, it is removed [45]. The parameters affecting process and component quality are feed rate of materials, reflectivity of materials, melting point of feedstock, laser power and scanning speed of laser. By adjusting these parameters, there is a wide range of flexibility in fabricating different materials. The only deficiency of LENS compared to SLM is its lower geometric accuracy that requires post-processing such as high-speed machining. Also, it has been mentioned that in some complex parts, a finalizing heat treatment is essential. All being said, the most significant benefit of this process is that it can deposit materials in spots that need to be filled As an instance, in expensive forming dies and molds, if there is a hole, crack or any other physical problem, it can be easily filled with a desired material using LENS [46]. Figure 6 represents a schematic layout of LENS process.

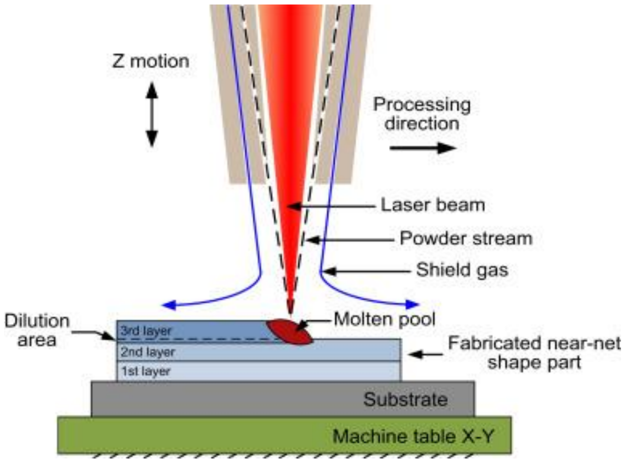

Figure 6: Laser engineered net shaping (LENS) process [47]

Binder Jet Printing (BJP)

Binder jet printing (BJP) is a typical form of AM processes that is mostly used for metals. However, there are many reports of polymeric and ceramic materials utilization[48]. The same as SLM and LENS, this process has a computer-controlled head which injects ink of adhesive materials. On the other side, a roller or coater similar to the one in SLM, will bring a uniform thickness of materials into the fabrication chamber. In the next step, the spread material will receive amounts of adhesives in the geometry of the specific slice of the 3D CAD file [49, 50]. As it is obvious, the difference of this process with the last two is that instead of using a laser head to melt the powder, it uses an adhesive injector head to bond the materials. After all the layers are deposited and bonded with adhesives, the part is finished but not completed yet. The final step of fabricating BJP parts is to cure them in a specific heat in a furnace. The curing temperature varies based on the adhesive and base materials used [51]. However, it has been mentioned that some new BJP equipment are in lab scale that apply heat and cure the adhesives after each layer has been deposited. Furthermore, in some ceramic materials, there is a need of high temperature firing in order to attain the specific properties of the ceramic materials. The density of the parts made in this process strictly depends on the particle size of powder feedstock. The smaller the powder size, the higher the density [52]. It has been reported that densities over 99% are achieved during BJP. Another capability of BJM is that it is able to provide colored structures such as the ones that are used in educational purposes. However, this advantage is still limited and needs more investigations. Regarding surface quality of the BJP-fabricated parts, they usually need to undergo finishing and machining process in order to remove surface roughness and fluctuation in flatness [50]. It has been mentioned that hot isostatic pressing has been implemented on BJP-fabricated parts to improve surface quality and density. Figure 7 represents a schematic BJP process.

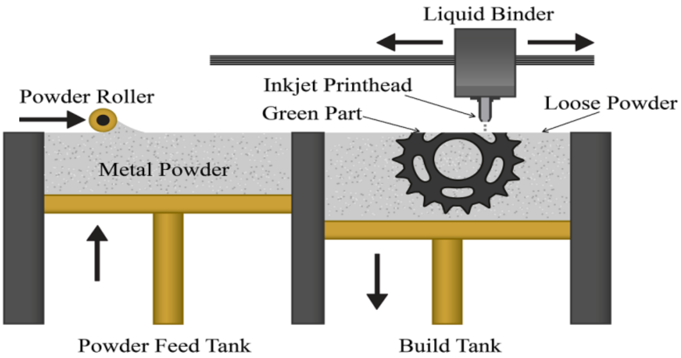

Figure 7: Schematic view of a binder jet printing setup [53]

Summary

In summary, additive manufacturing processes are categorized as the advanced types of manufacturing techniques that utilize simple but precise rules of manufacturing. In all these processes, a source of feedstock is available in different forms of wires, rods, powders and large particles. Based on the needs of a part and a method of fabrication, a technique is selected. However, a more general categorization leads to two distinct categories of polymeric and metallic materials. The processes that are for polymeric materials are usually unable to have performance on metallic and ceramic materials while the opposite is not true. In many processes of metallic materials, the polymeric materials are considered as secondary sources of feedstock. However, there should be considerations regarding suitability of these processes since high generated heat of laser and other sources of metal forming and deposition might have negative effects on polymers and plastics. Up to now, the parts obtained in different types of AM processes provide a high density even close to the regular base materials and better properties compared to the conventional materials as during the process and after that, they undergo different steps of curing, heat treatment and mechanical treatment. All being said, it is safe to conclude that AM processes are going to be the superior manufacturing methods and they will replace conventional techniques However, there is still more research and investigation needed in different aspects of AM.

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