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Literature Review: Summarization of Recent Additive Manufacturing of Polymers and Prospective.

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Abstract

This Literature review seeks to summarize the current additive manufacturing methods and commercially available polymers generally used in additive manufacturing to better understand how to incorporate sustainable and environmentally friendly materials into additive manufacturing without compromising the structural integrity of the final product. This paper also investigates and summarizes the advantages and disadvantages of the most commonly used polymers and concludes that in order to find the best polymer to use for a certain project 3 areas should be considered, namely consumer needs, environmental considerations and public health considerations. Furthermore it was concluded that deciding which polymer is best for a project involving additive manufacturing should be done on a case-by-case basis, as there is no polymer that can conform to every additive manufacturing application. Finally this literature review highlights and summarizes the issues that are encountered both in the additive manufacturing process and in the available polymers in order to serve as a fundamental building block for further research.

1. Introduction

Additive manufacturing, generally referred to as 3D printing, is a production method to manufacture three-dimensional objects normally by depositing materials layer by layer. Additive manufacturing refers to creating an object by adding material. 3D printing refers to creating an object by layering material on top of itself using a machine and CAD software. Though 3D printing is normally considered as the non-technical term of additive manufacturing, the two definitions are not entirely synonymous, emphasizing that 3D printing is based on the layering technique while additive manufacturing is overarching, encompassing manufacturing methods such as 4D and 5D printing. This has many different applications within our lives. For example Material extrusion is an additive manufacturing technique which feeds a continuous thermoplastic or composite filament through an extruding nozzle and then deposits it onto the surface layer by layer. It can produce things such as car bearings, gaskets and bumpers (Wu et al., 2021). Vat photopolymerization is another additive manufacturing technique that creates 3D objects by selectively curing liquid resin using UV light, to produce things such as surgical implants using silicone.

Additive manufacturing has become an important force in industrial and home-based manufacturing, gradually replacing heavy-duty machines that may require several operators. However, despite the many benefits additive manufacturing offers, it is imperative to note that certain polymers such as Acrylonitrile butadiene styrene (ABS) are produced from oil and are therefore not environmentally friendly. ABS is commonly used in household appliances and toys and is one of the most commonly used plastics (Ziemian et al., 2015). Production of ABS depletes our finite supply of oil, produces greenhouse gases which contribute to global warming and contributes to harmful microplastics found in coastal areas (Bai et al., 2019). This sustainability issue as well as many other issues of additive manufacturing, such as low production rate or poor resolution (Zhou et al., 2020), are aspects that need to be worked on in the future development of additive manufacturing. However, to explore potential solutions, a detailed yet concise summary of recent additive manufacturing methods and related materials is required to have a solid building block in this field.

Thermoplastics and thermosets are two major categories of polymers. Thermoplastics are polymers which can be re-melted several times and reused for different purposes, thermosets on the other hand are polymers that are irreversibly hardened from a liquid state. The latter primarily uses resins at the initial liquid polymer. In the following review, we will be focusing on additive manufacturing methods which use polymers as feedstock, highlighting the significance of environmentally friendly thermoplastics, and provide some discussions on the prospective development of additive manufacturing. .

2. Additive manufacturing Methods and Polymers

2.1 Importance and Purpose

In this technologically advanced world where new innovations are constantly being realized, it becomes harder and harder to create novel ideas. This situation is especially exacerbated if one does not have a clear picture of what has already been created in order to begin to build on top of it. This literature review seeks to build that foundation in the field of additive manufacturing, by summarizing recent publications to understand what is already known in this field and identify the current challenges. The literature review gives a clear picture to any new problem solver.

The topic of this paper holds a dual importance. Understanding the problems of additive manufacturing is of high priority to ensure application of additive manufacturing on large functional items such as cars, houses or even body parts is feasible. Disadvantages of additive manufacturing, such as low printing resolutions, slow printing speeds (Zhou et al., 2020), printing offset or cracks in long or tall structures (Marinescu et al., 2018), are all current problems which are still faced today and inhibit widespread manufacturing using this additive manufacturing method. The second important topic of the paper is the polymers used by additive manufacturing methods as wise selection of materials can improve environmental sustainability of additive manufacturing and benefit public health. Currently one of the most common polymers used in additive manufacturing is the oil based and environmentally unfriendly ABS. In fact Liu *et al.,* (2016) also reported that ultrafine particles emitted from the printing of ABS could be a possible "health risk, especially for those with asthma".

2.2 Methods

The main categories of additive manufacturing are established in standard ISO/ASTM 52900. The breakdown of additive manufacturing is presented in a hierarchy chart as shown in Figure 1 (located in the appendix). The main categories of additive manufacturing are material extrusion, material and binder jetting, vat photopolymerisation, sheet lamination, powder bed fusion and direct energy deposition. These categories were further separated into additive manufacturing methods generally employed in the industries or reported in the papers and finally into the corresponding materials used. Figure 1 clearly depicts the overlap of the materials used by each process and distinguishes the principle manufacturing techniques adopted in each method.

After categorizing the manufacturing methods, some common polymers used in additive manufacturing are summarized to compare their advantages and disadvantages including cost, environmental sustainability and mechanical properties, and present their common applications. Each polymer was evaluated in Table 1 located in the appendix.

Table 1 summarizes the properties of each polymer and the key ideas that pertain to this review from the referenced papers. For example, two resins used in Vat photopolymerization both belong to thermosets and as such they share some common qualities, which include the ability to withstand higher temperatures as well as the hardness of the final product. Meanwhile, there seems to be notable differences between these two resins, such as the amount of water absorption, potential hazards and even cost effectiveness. These unique properties differentiate their applications and durability.

A similar set of similarities and differences leading to unique usages is seen with thermoplastics specifically between Polylactic Acid (PLA) and ABS. They mirror each other closely in additive manufacturing methods used and resistance to chemical corrosion, but differ greatly in cost effectiveness and environmental friendliness - these two factors seemingly have an inverse relationship (this can be further seen in the appendix). This leads to their unique usages in different industrial applications.

2.3 Implications

There are several different key themes that can be gathered from this paper. One of the most vital aspects is that the additive manufacturing method and respective polymers that are quote “necessary” for the job are very much unique and customized to the consumer. For example, Taranu *et al.* (2018) mentioned that lack of water absorption for polyester can be a disadvantage as it would pertain to textiles, however, Oromdroyd *et al.* (2015) defined nearly the exact opposite as a disadvantage of Urea Formaldehyde resin saying that high water absorption was in fact negative in producing wood based composites. Even though they both have thermosetting properties depending on what the final product will be, the best polymer will vary. This serves to greatly emphasize the importance of evaluating each material on a case-by-case basis for different applications and targets.

On the other hand, this literature review also addresses the importance of taking environmental sustainability and public health into consideration when selecting the polymers used in additive manufacturing because they are at the forefront of global challenges to ensure a better future for humanity. For example, as previously mentioned in the paper by Ziemian et al., (2015), one of the disadvantages of ABS was that it was an oil based product and can be very harmful to the environment. In addition, producing ABS could pose a threat to our finite supply of oil which has many other applications. However, building on top of this, Mohammed et al., (2020) began to do trials of using 100% recycled abs for additive manufacturing and therefore achieved circular production. Certain limitations were stated such as the fact that “degradation in mechanical properties during tensile tests and a decrease in the polymer melt flow, which required reduced raster speed to achieve repeatable prints”. These limitations in turn will provide the fundamental building blocks for future researchers. It should also be noted that the authors emphasized that “recycling and reprinting is possible with acceptable loss of material integrity” which once demonstrates the case-by-case basis that recycled ABS could be used for.

Figure 2 - Venn Diagram of different implications. (The yellow star in the center indicates the best polymer possible that has taken into consideration all three impacts.)

In order to clarify the implications of the case-by-case basis for choosing the correct polymer and additive manufacturing method for specific application, a Venn diagram has been shown in Figure 2 with a summarization of the key considerations from different perspectives.

3. Conclusions

In summary, this review is a critical step to accelerate the growth of additive manufacturing methods so that it can play a dominant role in production at various scales. A hierarchy chart was presented to define the different additive manufacturing categories, the methods under each category, and the associated materials. From the identified categories, additive manufacturing methods which used polymers were further analyzed by classifying the polymers into thermoplastics or thermosets for comparison. Numerous journals were reviewed to identify the advantages and disadvantages of each polymer. The information was then summarized in a table further served to elucidate the environmental, public health and sustainability challenges that needed to be addressed to further the field of additive manufacturing. This included issues such as lack of functional sustainable polymers with comparable mechanical properties for high-end applications, the inverse relationship between cost effectiveness and environmental friendliness, and the degradation of certain mechanical properties if the polymer was recycled.

Furthermore, this paper accounted for the potential issues with the recent additive manufacturing methods such as cracks in tall structures, printing offsets, missing layers, and the slow speed of the printing process which caused large energy wastage. The implications of the requirements for certain additive manufacturing methods and the consequential lack of adequate polymers that fit all these expectations were also discussed within this review. This review lays a solid foundation for understanding the recent development of additive manufacturing methods and offers an insight into present challenges that require further investigations.

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Appendix

Figure 1

Hierarchy chart detailing the different additive manufacturing categories created by author on Lucidchart

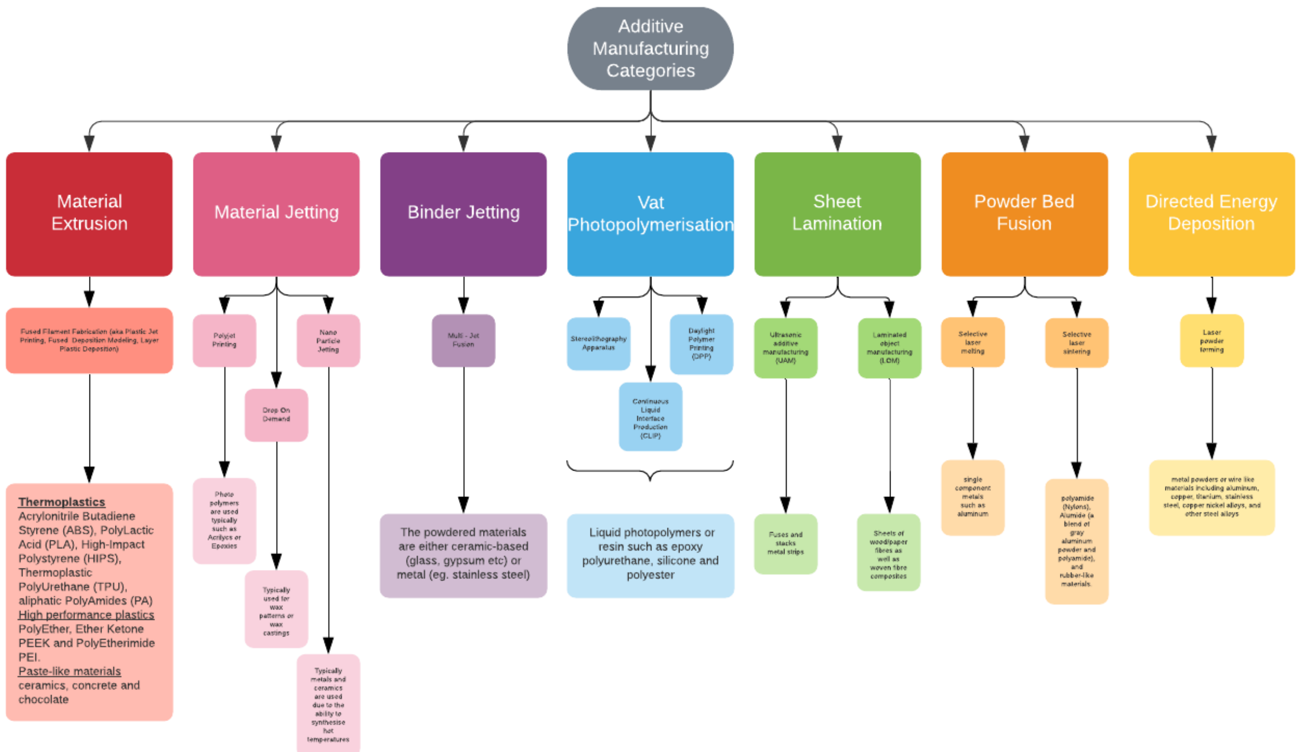

Table 1

A Summarization of Various Polymers Commonly Used In 3D Printing. Table created by author using google docs.

Polymer	Associated Printing Method	Classification	Advantages	Disadvantages	Common Applications	Reference
Thermoplastic polyurethane (TPU)	Material Extrusion (fused filament fabrication)	Thermoplastic	Abrasion resistance Excellent impact strength Tough and flexible Elastic versatile and resistant to impacts, tears, abrasions, weather and hydrocarbons. can be used as both a hard rubber and a soft engineering thermoplastic. low temperature flexibility Some TPU grades exhibit biocompatibility, optical clarity, hydrolytic stability and flame retardant or anti-static properties which can be used for varying purposes Can be sterilized and easily processed Can also be welded, painted, printed and die-cut.	Some grades of TPU have a short shelf life Drying time is required beforehand Not as cost-effective as other alternatives	car bumpers bearings gaskets belts containers protective coverings for phones computer components floatation devices glass frames and handbags	[1]

Thermoplastic olefin (TPO)	Material Extrusion (fused filament fabrication)	Thermoplastic	Similar advantages to TPU (see above) as they are both elastomers Nontoxic Very light weight Chemically inert Better impact resistance than standard Polypropylene grades, at low temperatures do not require drying prior to molding → saves on both cost and time.	Cost of TPO is slightly higher Decreased performance at elevated temperatures Lower stiffness than TPU which could be harmful to performance	specialty food and pharmaceutical packaging medical IV bags and tubing hoses and pipes wire and cable insulation Extensively used in vehicles (eg. armrests, dashboard skins, floor mats etc)	[2]
Epoxy resin	Polyjet Printing Vat Photopolymerization	Thermoset	Good mechanical properties (tensile strength,compression etc.) Resistant to high temperatures Good physical properties even in a moist environment Chemically resistant Adheres on a wide variety of materials Low shrinkage (1%)	Require a long polymerization time Susceptible to cracking Not very cost effective as compared to other resins Needs strict conditions to be used properly Aggressive on skin (hazard) Harmful sanding dust (hazard)	Flooring panels Ducting Vertical and horizontal stabilizers Wings Lightweight parts for automobiles Bicycle frames Golf clubs Racing cars	[3]
Urea formaldehyde (UF) resin	Polyjet Printing Vat Photopolymerization	Thermoset	Higher maximum operating temperature Good hardness Low	Lower Tensile strength Higher water absorption (hydrolytic degradation)	Flower arranging blocks Insulating panels Wood-based	[4], [5]

			flammability Colorless Relatively inexpensive	Higher Shrinkage	composite panels eg. plywood	
Nylon	Material Extrusion (fused filament fabrication)	Thermoplastic	High tensile and compressive strength Good impact strength High Softening point Low friction coefficient Resistant to Chemicals	Poor water absorption *could also be helpful Poor dimensional stability Becomes brittle at low temperatures	Textiles fishing line Carpets food packaging car engine components.	[6]
PVC	Material Extrusion (fused filament fabrication)	Thermoplastic	Non Flammable Versatile Insulative properties Water resistant Relatively chemically and UV resistant Cost effective Flexible	Not suitable for higher temperatures When burned toxic fumes produced (hazard)	window frames drainage pipe medical devices cable and wire insulation automotive interiors and seat coverings Packaging and cling film synthetic leather	[7]
Polypropylene (PP)	Material Extrusion (fused filament fabrication)	Thermoplastic	Relatively cost effective High flexural strength Resistant to moisture Resistant to chemicals Good impact strength Insulative properties	Limited high temperature applications Susceptible to UV degradation Poor bonding Highly flammable (hazard) Susceptible to oxidation	syringes medical vials Petri dishes pill containers specimen bottles battery casings trays and drink	[8]

					holders Bumpers ropes, twine, tape, carpets, upholstery, clothing etc.	
Polystyrene (PS)	Material Extrusion (fused filament fabrication)	Thermoplastic	Cost effective Can accommodate fine detail. Variety of colors or colorless Insulative properties Chemically inert Very versatile	Flammable (hazard) Low tensile strength; brittle Not biodegradable	food packaging laboratory ware Appliances Electronics automobile parts Toys gardening pots equipment Expanded Polystyrene (foam) can also be used for home insulation, lightweight packaging, surfboards etc.	[9]
Polylactic acid (PLA)	Material Extrusion (fused filament fabrication)	Thermoplastic	Can be printed on a cold surface – More environmentally -friendly Shinier and smoother appearance No harmful fumes during printing Higher 3d printer speed More detail	Can deform because of heat Lower tensile strength in comparison to ABS Costs more than ABS Permeable to water	Tissue engineering scaffolds PPE Textiles Packaging Medical sutures Bone screws Other biological applications in the dental and cardiac fields	[10]
Acrylonitrile butadien	Material Extrusion (fused	Thermoplastic	Very sturdy and hard Suitable for	Made out of oil, so more damaging to	computer keyboard components	[11]

e styrene (ABS)	filament fabrication)		machine or car parts Higher melting point Longer lifespan High tensile strength Resistant to impacts and chemical corrosion	the environment Deforms when not being printed on a heated surface Hot fumes when printing (ventilation needed) (hazard) Not food grade Low melting point	plastic face guards for wall sockets decorative interior car parts plastic tubing hard hats and helmets Printers vacuum cleaners kitchen utensils plastic toys	
Silicone	Vat Photopoly merization	Thermoset	High heat resistance Non porous - (food grade) Water resistant Non toxic Flexible	Low tensile strength Low resistance to abrasion Higher cost	heat-resistan t seals Gaskets electrical insulators flexible molds Surgical implants Household items Adhesives	[12]
Polyeste r	Vat Photopoly merization Material Extrusion (fused filament fabrication)	Depending on the situation it could be both a thermosetting resin and a thermoplastic	More cost effective than epoxies Low Viscosity Shorter Curing period	Water permeable Off-gases VOCs and strong, flammable fumes Brittle and prone to micro-crackin g Low Bonding Strength Higher shrinkage	Fabrics - Textiles that do not shrink or wrinkle Can also be used for ropes carpeting etc	[13]