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Polymer 3D Printing: A review of techniques with their advantages, limitations, and industrial applications

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Abstract – Additive manufacturing is one of the modern and rapidly developing technology that has great potential to transform the manufacturing industry. It involves the layer by layer deposition of materials to create three dimensional objects directly from a digital model, making it possible easily produce highly complex and intricate designs. Nowadays, polymer 3D printing is one of the most popular fields of additive manufacturing technology, which uses several techniques to print parts using polymers or plastic materials. Several types of polymer 3D printing techniques are thoroughly reviewed in this study, along with their benefits, limitations, and industrial uses. Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Layer Sintering (SLS), and PolyJet are the four main techniques that are covered in detail. Each method is discussed in detail, along with its working principle, benefits, and drawbacks. Furthermore, the current research work examines the industrial applications of polymer 3D printing, which include the aerospace, automotive, medical, and consumer goods industries. The mentioned industries have taken advantage of special capabilities of 3D printing to produce complex parts with more design flexibility, improved efficiency, and lower costs. The paper provides concrete instances of how 3D printing has been implemented across various industries, along with the advantages it has yielded. It was aimed that this review will serve as a valuable resource for researchers and engineers who are interested in the potential of polymer 3D printing technology in modern manufacturing.

Keywords – Plastic 3D printing, Additive manufacturing, FDM, SLA, SLS

I. INTRODUCTION

3D printing technology, also referred to as additive manufacturing, is a promising solution that has emerged for producing complex and customized products. Plastic 3D printing is a popular choice and is preferred to use because it is very versatile and cost-effective technology. This technology involves the layer by layer deposition of thermoplastic material to form a three dimensional part. The generation of the digital model by using computer-aided design software is the starting step of the printing process. The software then slices the digital model into horizontal layers, which are then uploaded to the 3D printer machine [1]–[4].

Extrusion based 3D printers use a nozzle to deposit the plastic material, layer by layer, onto a build platform. To start the printing process, firstly, the polymer material is heated until getting it in a molten liquid state and then pushed out through the nozzle in a controlled manner. The printer head moves in the x, y, and z directions to deposit the polymer material layer by layer, following the pattern of the sliced model. When the printing process is getting done, the produced part is left to cool and solidify [5], [6].

The available technologies for polymer 3D printing are fused deposition modeling [5], stereolithography [7], and selective laser sintering [8]. Fused deposition modeling is the most common plastic 3D printing technology and involves the deposition of melted thermoplastic material through a heated nozzle. In the stereolithography technique, the laser is used for solidifying a liquid resin into a solid object, while selective laser sintering uses a laser to sinter powdered plastic into a solid object [5], [7], [8].

Regularly used materials are thermoplastics because of their processing simplicity, low cost and expanded range of mechanical properties. Polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), nylon and etc are common examples regarding to thermoplastics. Each of the material has various strength, flexibility, and temperature resistance properties which can be selected based on the needs of final part [5], [6], [9].

There are several advantages that polymer 3D printing offers compared with conventional manufacturing methods such as more efficient production, great flexibility in design, less lead times and etc. However, the quality of the final part, the limited size of the printing bed, and the availability of suitable materials should be noted as limitations of this technology. Furthermore, various industries like aerospace, automotive, biomedical, consumer products, etc. actively implement this technology. This particular technology is commonly utilized for prototyping and verifying designs. However, it is also gaining popularity in the creation of final products such as dental implants, prosthetics, and parts for aerospace and automotive applications [10]–[13]. The purpose of this research paper is to give a thorough examination of various 3D printing methods that involve polymers, such as Fused Deposition Modeling, Stereolithography, Selective Layer Sintering, and PolyJet. The paper aims to discuss the pros and cons of each technique and how they are used in different industrial applications. The research work also aims to explore the various industries that utilize polymer 3D printing technology, such as aerospace, automotive, medical, and consumer goods. Ultimately, this paper intends to provide help readers comprehend how polymer 3D printing technology can be used in industrial applications and the effects it could have.

II. Types of Polymer 3D Printing Techniques

A. *Fused Deposition Modeling (FDM)*

Fused Deposition Modeling is a widely used additive manufacturing technology for producing plastic parts with complex geometries. Fused Deposition Modeling technology is both cost-effective and user friendly, which has contributed to its widespread adoption in both industrial and personal settings. This literature review will cover the fundamental concepts behind FDM technology, highlighting both its advantages and limitations, while also delving into the latest advancements in FDM research. FDM technology is based on the extrusion of a thermoplastic filament through a heated nozzle onto a build platform layer by layer. The thermoplastic filament is melted in the nozzle and extruded onto the build platform as a molten thread. When a hot and liquid material cools down and becomes solid, it sticks to the layer below it and eventually creates a three-dimensional and solid shape. The build platform is lowered after each layer is deposited to create a new layer. This particular technology has numerous benefits such as being affordable, user-friendly, adaptable, and more. Fused Deposition Modeling is a technique that utilizes various types of thermoplastics to produce parts that possess distinct characteristics such as durability, pliability, and thermal resistance. In addition, parts with complex geometries can be produced by using this technology which would be difficult or sometimes impossible to manufacture using conventional methods. Despite its advantages, FDM technology has some limitations. One of the main limitations is its accuracy, which is affected by several factors such as nozzle diameter, layer thickness, filament quality and some of other production parameters. Additionally, the surface finish of FDM parts is often rough, which may require post-processing. The size of the objects that can be created using the technology is limited because of the limited build platform size on 3D printers [14]–[18].

B. *Stereolithography (SLA)*

Stereolithography is one of the technology that is used in plastic 3D printing. This technique utilizes a liquid photopolymer resin to produce parts with high accuracy and smooth surface finish. The SLA is a popular technique employed in many different fields such as aerospace, medical, and automotive industries because of it is capable of creating complex and detailed parts. SLA technology utilizes a liquid photopolymer resin that is cured using a UV laser or light source. The resin is selectively cured layer by layer to create a solid part. The process begins with the build platform submerged in the liquid resin. The UV laser or light source is directed at the resin, selectively curing the resin where the part is to be formed. The build platform is then lowered, and a new layer of resin is applied on top of the cured layer. The process repeats until the part is complete. SLA technology provides several advantages over other additive manufacturing methods, such as the ability to produce parts with detailed features, a smooth surface finish, and high precision. The technology is also capable of producing parts with a range of physical properties, including flexibility, stiffness, and toughness, by varying the photopolymer resin used. Furthermore, utilizing SLA can enable the manufacturing of several parts at once, leading to a decrease in both the production time and cost. Although its profits have been highlighted, there are also some drawbacks. SLA has a significant drawback, which is the high cost of photopolymer resin used in the printing process. This cost can be comparatively higher than other materials used in 3D printing. Additionally, SLA parts may require post-processing to remove excess resin and cure the final part. The size of the parts which are made by using SLA technology is influenced by the size of 3D printer machine [7], [19]–[21].

C. *Selective Layer Sintering (SLS)*

Selective Layer Sintering is a 3D printing technology that uses a laser or other energy source to selectively sinter powdered material, layer by layer, to create a solid object. In several sectors like aerospace, automotive, medical and others, the SLC process is widely utilized because of its potential to produce parts with complex geometries and a wide range of materials. The process begins with a layer of powdered material spread across the build platform. The energy source is then directed at the material, selectively sintering the powder where the part is to be formed. The build platform is then lowered, and a new layer of powder is spread on top of the previous layer. The process repeats until the part is fully printed. This technology has many profits over other 3D printing methods, including the ability to produce intricately shaped parts, use a variety of materials, and without the need for additional support structures. Additionally, SLS parts can be produced with high strength and durability, making them suitable for use in demanding applications. SLS technology is also capable of producing multiple parts simultaneously, reducing manufacturing time and cost. In addition, similar to other 3D printing techniques, SLS also has some limitations such as high cost of the equipment and materials, required post-processing to achieve better surfaces, and etc. [8], [22]–[25].

D. *PolyJet*

The PolyJet process involves the use of inkjet printheads to deposit photopolymer droplets layer by layer. The printheads contain hundreds of tiny nozzles that deposit droplets of photopolymer onto the build platform. The droplets are then cured by UV light, which solidifies the material and fuses it with the previously deposited layers. The process is repeated layer by layer until the part is complete. In addition to being faster than SLA, PolyJet comes with several other benefits. Firstly, it allows for the printing of different colours because it is a more controlled procedure. Moreover, unlike FDM and SLA techniques, the support structure does not need to be manually removed because it simply does not solidify during the process and can be washed or blown away. The 3D printed plastic parts produced by PolyJet technology have a high surface quality and can be elastic [24], [26]–[28].

Although its previously mentioned advantages, PolyJet technology has several limitations. These limitations contain the size of the parts that can be produced, and the parts produced using PolyJet technology may also be brittle, requiring post-processing to improve their mechanical properties [28], [29].

III. Industrial Applications

E. *Aerospace Industry*

Production of lightweight components with complex structures: Plastic 3D printing has a major benefit which is its capability to manufacture lightweight parts having complicated structures. In the aerospace industry, weight reduction is critical as it directly impacts fuel consumption and overall performance. Therefore, plastic 3D printing has become a popular option for producing lightweight components. For instance, Airbus is using 3D printed plastic parts in its A350 XWB aircraft. The company has developed more than 1000 flight parts for the Airbus A350 XWB that reduced the weight of the aircraft and improving fuel efficiency. Production of satellite components are another example for applications of plastic 3D printing in aerospace industry. The aerospace industry has also begun to explore the use of plastic 3D printing for satellite components. The European Space Agency designed a plastic antenna by utilizing 3D printing technology, which is lighter and more compact compared to traditional antennas. As a result, it's significantly cheaper to launch it on satellites. These antennas could contribute to the development of high-speed internet options, enhancing internet access for travellers on buses, trains, planes, automobiles, etc. Using high-frequency antennas in airplane designs could potentially enhance their aerodynamics and efficiency, which would lead to reduced fuel consumption during air transportation, ultimately lowering travel costs for everyone [30]–[33].

F. *Automotive Industry*

Prototyping: A commonly known illustration of 3D printing being utilized in the automotive sector involves using 3D printing technology to create prototypes. Several automakers, including Ford, BMW, and Audi actively using 3D printing technology to develop prototypes of their new vehicle designs. This method enables them to assess the vehicle's performance and aerodynamics before the actual production process starts [34], [35].

Lightweight parts with complex geometries: 3D printing has become significantly useful in the automotive industry by allowing the creation of lightweight parts with intricate geometries that are challenging to manufacture using conventional methods. A noteworthy illustration of this is how the BMW i3 electric car is manufactured using carbon fiber-reinforced polymers. BMW used 3D printing to produce carbon fiber-reinforced polymer components, resulting in to produce significantly lighter and more fuel-efficient vehicles. While maintaining the same strength, carbon fiber reinforced plastic is 50% lighter than aluminium and 30% lighter than steel [36]–[39].

Customization: 3D printing can be used to produce custom parts quickly and cost-effectively. One example of this is the use of 3D printing to produce custom trim pieces for the Porsche 911 and 718. Porsche used 3D printing to create customized trim pieces for the 911 and 718, allowing customers to personalize their vehicles with unique designs and colors [40], [41][40], [41].

Rapid tooling: The automotive industry has been a major adopter of polymer 3D printing technology for rapid tooling applications. 3D printing has enabled automakers and suppliers to produce tooling components such as jigs, fixtures, and molds quickly and cost-effectively, without the need for expensive and time-consuming traditional tooling methods. Automakers such as Volkswagen, BMW, Ford and Volvo use the possibilities of 3D printing technology for tooling. Rapid tooling using 3D printing technology has enabled the automotive industry to accelerate the design and production process, while also improving the overall quality and precision of the components produced [42]–[44].

G. *Medical Industry*

Polymer 3D printing has a great advantage in the medical industry as it can produce customized implants and prosthetics for patients. And this can influence the quality of life of patients significantly. 3D printing is especially useful for producing implants and prosthetics that fit perfectly to the patient's anatomy. This personalized approach can reduce the risk of complications and increase the success rate of surgeries [45]–[47]. Another promising application of polymer 3D printing is in tissue engineering. 3D printing can create precise and intricate scaffolds that can support cell growth and differentiation. These scaffolds can be used to regenerate damaged tissues. Although bone is one of the most often transplanted tissues, but there are certain drawbacks to using bone transplants. Pain at the donor bone location, a finite supply of donor bone, recipient rejection, pathogen transfer, and immunogenic reactivity are some of the mentioned drawbacks. Nowadays, fractures of the vertebrae and long bones are supported mechanically and structurally by metal implants, such as plates and screws. Pathogenic infection, stiffness, nondegradability, and extrusion are limitations of this approach. Scientists have been exploring advanced tissue engineering methods that involve using three-dimensional polymeric biomaterials to promote bone regeneration. This research is being carried out because traditional techniques have certain limitations [48]–[51].

Polymer 3D printing can also be used for drug delivery systems. 3D printing can create microstructures and nanostructures with controlled release properties, enabling targeted and sustained drug delivery. By using this technology, drug efficacy and safety can be improved by reducing the side effects that associated with conventional methods [52]–[55].

H. Consumer Goods

Customized product manufacturing is one of the main applications of polymer 3D printing in the consumer goods sector. Having the capacity to fast and efficiently produce individual designs, 3D printing made the mass customization of goods possible like jewelry, clothing, footwear, and others. For this reason, the companies can offer broader variety of products to provide spesific customer needs and preferences, leading to increased customer satisfaction and loyalty.In along with customization, 3D printing has been used to create exclusive and creative designs that would be not possible to make using traditional manufacturing techniques. The fashion industry has utilized the capabilities of 3D printing to fabricate complex and delicate shapes for fashion accessories, like sunglasses and handbags, for demonstrating the technology's ability to create exceptional and inventive designs. This resulted in the creation of novel and individual product lines that can distinguish the products of an organization apart from its competitors [56], [57].

IV. Conclusion

The review of different techniques, their advantages, and limitations presented in this paper demonstrate the potential of 3D printing in transforming the manufacturing industry. Among the additive manufacturing technologies, Fused Deposition Modeling is the most widely used technique due to its low cost, simplicity, and accessibility. As another popular technique, Stereolithography offers high resolution and accuracy in producing complex geometries but is limited by its high cost and limited material options. In addition, Selective Layer Sintering technology offers high mechanical strength, but its high cost and post-processing requirements make it less popular. In the final, as also known as InkJet technology, PolyJet comes with the ability to print in multiple colors and materials, making it suitable for producing high-quality prototypes.

Furthermore, the industrial applications discussed in this research study demonstrate the versatility of polymer 3D printing technology. The aerospace and automotive industries have benefitted from 3D printing by reducing lead times and producing lightweight and complex parts. In the medical sector, 3D printing has reformed the production of prosthetics, implants, and surgical tools. Consumer goods industries have used 3D printing to produce customized and personalized products.

In conclusion, polymer 3D printing offers significant potential for the future of manufacturing. With the continuous evolution and improvement of technology, it is highly probable that several industries will increasingly adopt 3D printing. While selecting the appropriate techniques for spesific applications, the advantages and the drawbacks of different procedures along with their industrial applications must be considered.

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