Gradus Vol 11, No 1 (2024)
ISSN 2064-8014

A COMPREHENSIVE REVIEW OF FUSED DEPOSITION MODELING (FDM) METHOD USING PLA, ABS, AND PET-G POLYMERS

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https://doi.org/10.47833/2024.1.ENG.007

Keywords:
3D Printing Materials, Additive Manufacturing, Material Properties, Material Selection, Additives in 3D Printing, Sustainability

Article history:
Received 30 March 2022
Revised 12 April 2024
Accepted 25 April 2024

Abstract
A notable increase in prominence has been observed in the application of Fused Deposition Modeling (FDM) 3D printing, resulting in a transformative influence on manufacturing processes in various sectors. The paramount importance of careful material selection for fully harnessing the capabilities of this technology is acknowledged. Within the scope of this comprehensive study article, an examination is conducted regarding the characteristics, benefits, and limitations associated with the three primary materials used in FDM 3D printing, namely Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyethylene Terephthalate Glycol (PET-G). Each of these materials is recognized for possessing unique characteristics that render them suitable for a diverse array of applications, including educational and creative pursuits, as well as industrial prototyping and the creation of functional components. Importantly, the potential to enhance the mechanical, thermal, and electrical characteristics of these substances has been demonstrated through the integration of additives, such as carbon nanotubes, nanoclay, and graphene. Through the cooperative efforts of material scientists, engineers, and 3D printing enthusiasts, it is anticipated that FDM 3D printing will emerge as an essential and invaluable instrument across a wide range of disciplines.

1 Introduction

A significant transformation in the manufacturing industry has been witnessed by 3D printing, also acknowledged as rapid prototyping, allowing for the production of intricate three-dimensional objects based on digital geometric models [1]. The idea's conception in the 1950s is attributable to Jim Bredt and Tim Anderson at the Massachusetts Institute of Technology (MIT) [2]. A significant advancement in this technological progression involves the integration of inkjet printers, enabling the deposition of materials in layers to create three-dimensional structures.

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The introduction of 3D printing in various sectors is linked to the granting of a patent for the first 3D printer in 1986, which was subsequently followed by its commercial availability in the 1990s [3].

2 Technology and material selection

2.1. 3D printing

In the category of additive manufacturing, the gradual deposition of small material layers in the 3D printing process is involved in the construction of items. As shown in Figure 1, first, the creation of a digital prototype is initiated, which can be accomplished through the utilization of computer-aided design (CAD) software or 3D animation applications. Alternatively, a digital representation of pre-existing artifacts can be produced through scanning techniques. The models are subsequently divided into horizontal layers with consistent thickness, typically saved in STL file format, in which the three-dimensional surface is approximated using minuscule triangles. Improved accuracy in this approximation is achieved as the size of the triangles is reduced. The printing process involves the use of model data to generate successive layers that overlap with one another. The duration of the printing process is contingent upon the dimensions and intricacy of the item, spanning from a few hours to several days. There are many technologies available for layering, including Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS), which are widely utilized in the field. Currently, the use of 3D printing technology has been seen in a diverse range of sectors, including jewelry, art, architecture, automotive, aerospace, education, healthcare, and digital dentistry. This widespread adoption has extended the scope of 3D printing beyond its initial application in toy manufacture [4].

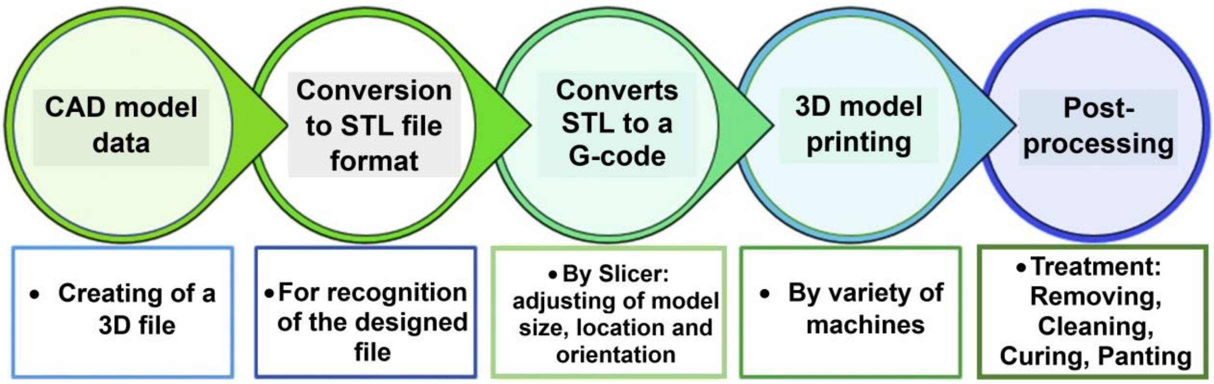

Figure 1. Schematic representation of the typical stages involved in 3D printing [5]

FDM is considered the most prevalent technique for plastic fiber fusion among other 3D printing methods. According to available literature, it has been established that Stratasys now has the patent for FDM technology. This particular technology exhibits the capability to fabricate concept models, prototypes, as well as functional components using a range of thermoplastics, including standard, engineering, and high-performance variants [6]. Murariu and Dubois (2016) underscored the adaptability of FDM by emphasizing its capacity to use a diverse array of plastics, including those often employed in injection molding [7]. This characteristic renders almost every thermally meltable and extrudable material appropriate for 3D printing (see Figure 2), such as Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). The benefits of FDM were highlighted by Algarni and Ghazali (2021). These advantages include cost-effective raw materials, the instant acceptability of printed products for end-use, and the capability to adjust wall thickness and infill density in order to produce lightweight but robust components [8]. Nonetheless, this technology is associated with several constraints, such as a printing procedure that is more sluggish and labor-intensive, increased visibility of layer lines, and the presence of residual support material on untreated printed products [9].

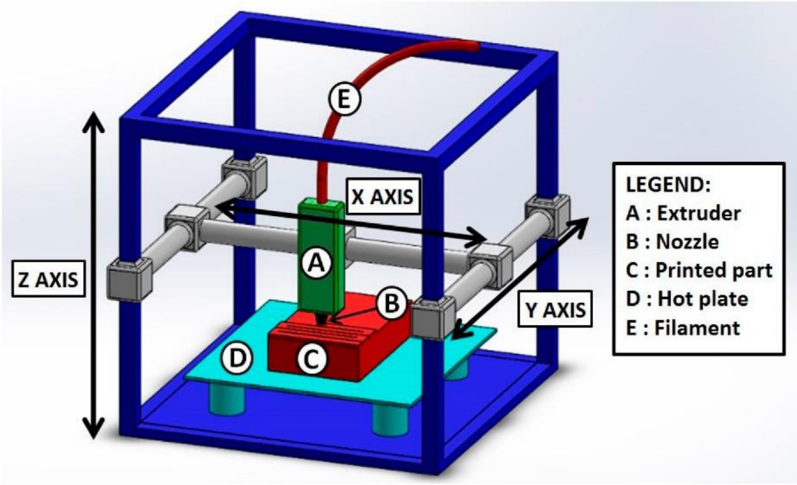

Figure 2. Illustration depicting the configuration of a standard fused deposition modeling (FDM) system [10]

The segmentation of a three-dimensional (3D) model into distinct layers through the utilization of slicing software is involved in the FDM procedure. Concerning their thickness, these layers have the capability to be adjusted. A file is generated by the software, which is then utilized by the printer. Upon heating the printing surface and initiating the extrusion of the specified material, the printing procedure is set in motion. A layer-by-layer deposition process is employed to conduct the deposition until the entire item is fully printed, following which it is subjected to cooling for subsequent removal. An investigation into the utilization of raw materials in the FDM technique was undertaken by Cai et al. (2022), with particular attention to their qualities that exert influence on the utilization of printed objects [11].

Significant consideration is given to the materials for FDM printing, and their selection is influenced by various parameters, including the temperature constraints of the printer, the conditions within the chamber, and the specifications of the nozzle. Materials like PLA, ABS (see Figure 3), and PET-G are limited in availability due to the constrained temperature range of 220-250°C. Their selection was driven by their distinctive characteristics: PLA was favored for its biodegradability, ABS for its applicability as an industrial plastic, and all three were deemed suitable for use as carrier materials [12]. The potential inclusion of additives such as graphite, magnesium, and silicone oil was also contemplated, although further research is necessitated to ascertain their impact [13].

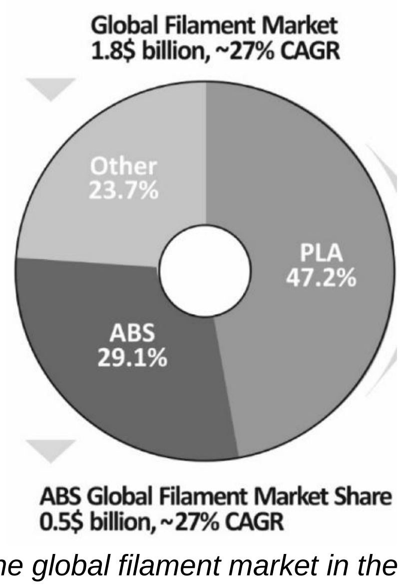

Figure 3. Volumetric data for the global filament market in the field of 3D printing for the year 2019 [14]

2.2. General properties of the basic materials to be used

2.2.1. PLA

A multifaceted thermoplastic polymer known as polylactic acid (PLA) can be produced from various sources, including renewable feedstocks (see Figure 4). PLA exhibits environmental friendliness owing to its capacity to undergo biodegradation under certain circumstances. The product provides a level of transparency and may be easily modified to achieve desired aesthetic outcomes. In contrast to ABS, the material in question exhibits less flexibility and impact strength, albeit possessing more rigidity. The product has exceptional cold resistance, making it appropriate for storage under low temperature conditions [15]. PLA is extensively used in the field of 3D printing owing to its exceptional printing characteristics, satisfactory mechanical strength, and environmentally benign attributes. The popularity of it may be attributed to its inherent qualities of renewability and biocompatibility. The average tensile strength is around 73 MPa, accompanied by an elongation at break of 5% and a melting point of 175°C [16]. The utilization of PLA in medical and consumer items has garnered acknowledgement, notwithstanding its inherent drawbacks concerning brittleness and flexibility. These limits may be ameliorated by including additives [17]. Bhagia et al. (2021) highlight the adaptability of PLA in biodegradable applications. They also discuss the possibilities for improving its characteristics by using additives, such as cellulose [18]. Furthermore, researchers have explored the incorporation of coffee grounds and other materials into PLA, providing valuable insights into the impact of these additions on the characteristics of the composite material [19]. Future investigations might go into the examination of composites based on PLA with varying additions and compositions.

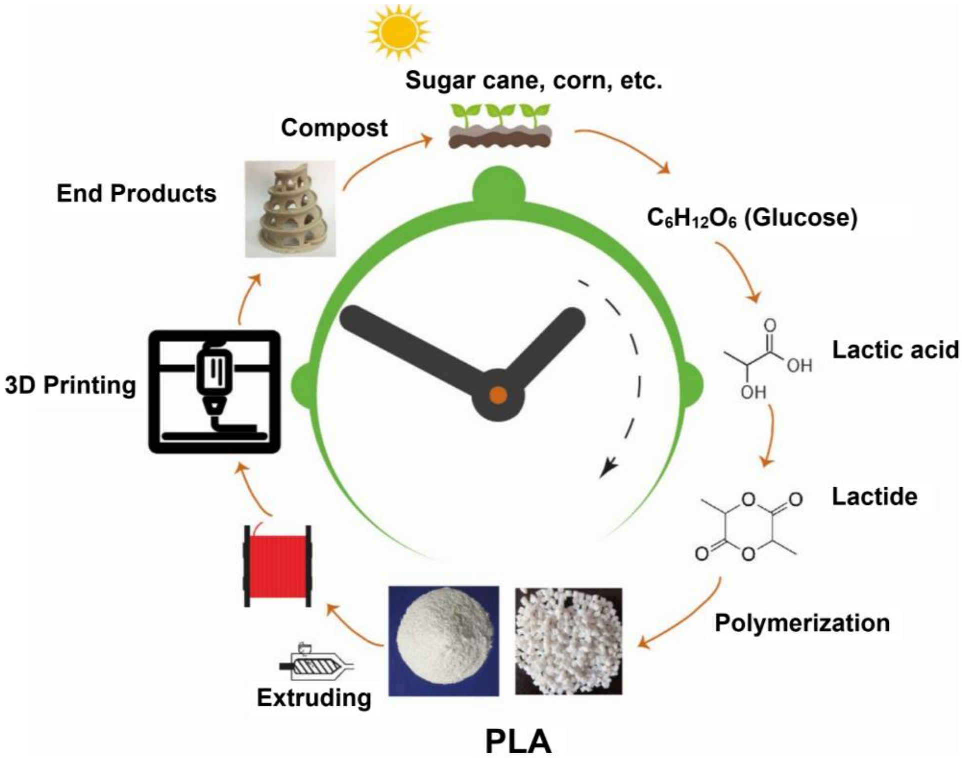

Figure 4. Lifecycle of Eco-friendly Polylactic Acid (PLA) [20]

In 2021, an investigation was carried out into the production of composites consisting of amorphous magnesium phosphate (AMP) and PLA using 3D printing [21]. It was noted in the findings that an unfavorable influence was observed on the mechanical attributes of PLA upon the introduction of AMP. It is recommended to pursue further research to examine different compositions and their impact on the material's attributes. In 2022, PLA-graphite composites were explored within the context of FDM 3D printing [22]. Considerable attention was given to the potential enhancements concerning mechanical, biological, thermal, and electrical properties. A notable enhancement was demonstrated in both the material's glass transition temperature and degree of crystallization. Further examination is deemed necessary to explore the consequences of variations in additive concentration and composition. Maurel et al. tested high-load graphite-PLA composite with FDM technology [23]. They wanted to use it in a lithium-ion battery, because the utilization of the Li-ion battery is very high these days, and they wanted to find a new solution for the production of electrochemical systems. To extrude the filament, PLA pellets and graphite were used as the active material for the negative electrode of the lithium-ion battery, and 4 x 4 mm pieces of composite film were made from a filament with a diameter of 1.75 mm - which had been previously extruded. Differential scanning calorimetry, Raman spectroscopy, and scanning electron microscopy were used to examine the material, as well as mechanical characterization, electrical conductivity characterization, and electrochemical characterization.

Filaments were produced by Zerankeshi and Alizadeh in 2022 [24]. Due to its physiological effects, the composite is intended to speed up healing processes. PLA and graphite have hydrophobic properties, but magnesium is hydrophilic. In the article, the effect of magnesium added to the graphite-PLA polymer was investigated, taking into account the mechanical, thermal and structural characteristics. The composites contain 1% by weight of magnesium and 1% by weight of graphite, and their particle size is smaller than 45 μm. 15 mL of DCM was added to the mixture and magnetically stirred for 10 min - until a homogeneous solution, then heated in an oven at 100 °C for 12 h to evaporate the DCM. The filament was then extruded at 190 °C for 1.75 mm diameter printing. The following methods were used to analyze the composite: differential scanning calorimetry, X-ray diffraction, tensile test, contact angle test, scanning electron microscopy. Hanon et al. (2020) tested the mechanical properties of different printing directions with bronze-PLA composites [25]. Its aim was to demonstrate how the mechanical properties can be influenced in the orientations of the different printing layers. 3D printing, tensile testing, tribological testing were used to produce samples with different layers, and hardness and surface roughness were measured with an optical microscope. Bronze plays a significant role in improving the tribological properties of polymer composites – it has been reported that bearings made of 60% bronze-reinforced polymer composites have reduced adhesive wear marks. In 2020, the use of cellulose as an addition in PLA for FDM-printed composites was examined [26]. The inherent capacity of cellulose to augment the mechanical and thermal characteristics of the material was elucidated. The comprehensive investigation of the project included several analytical techniques such as tensile testing, scanning electron microscopy, and thermogravimetric analysis, with the aim of examining the mechanical and thermal characteristics. To effectively rival conventional materials, optimization of the characteristics of composites based on PLA is considered essential. Addressing several restrictions, including mechanical strength, thermal stability, and bioactivity, may lead to the expansion of PLA composite applications and facilitate their general acceptance.

2.2.2. ABS

The thermoplastic polymer known as Acrylonitrile Butadiene Styrene (ABS) is frequently employed in the FDM process for 3D printing. The object in question is widely acknowledged for its exceptional strength, ability to endure external forces, and long-lasting characteristics. Although it may not possess the same level of environmental friendliness as PLA, it is worth noting that this material is really recyclable. ABS has commendable thermal resilience, making it appropriate for applications involving high temperatures [27]. The selection of ABS as a material for 3D printing is mostly influenced by its mechanical characteristics. The material has a tensile strength of around 27 MPa, a fracture strain of 30%, and a glass transition temperature of 105 °C. Nevertheless, this material is prone to warping and necessitates the use of a heated bed or an enclosed print chamber in order to address this concern [28].

Further research potential include the use of ABS-based composites to investigate their impact on mechanical, thermal, and electrical characteristics. Many articles deal with the tribological properties of pure ABS, but its addition and its effects are not yet fully understood.

Researchers investigated the effect of epoxy coating on the properties of pure ABS filament, which is a thermosetting polymer commonly used to produce adhesives, coatings and matrix resins for composite materials [29, 30]. As a surface treatment, epoxy can improve mechanical properties such as tensile strength or modulus of elasticity, as well as thermal and chemical resistance, and epoxy fills the pores of materials well [31]. The pure ABS material has a yield strength of 31.19 MPa and a tensile strength of 50.96 MPa, while that of the surface-treated version was 41.9 MPa and 85.72 MPa [32].

A. de León et al. (2019) added polyurethane to ABS, creating a copolymer by extrusion at 230°C. Polyurethane is also a thermoplastic, the compounds are well mixed together [37]. The results were very varied: below 10% polyurethane content, the elongation at break decreased compared to pure ABS polymer, but above 20% polyurethane content, it showed a higher value, so polyurethane can increase the deformability of materials. The yield strength values have not changed. These enhancements are thought to have the potential to expand the range of applications for ABS within the domain of 3D printing.

2.2.3. PET-G

A polymer known as polyethylene terephthalate glycol (PET-G) has been increasingly utilized in the realm of 3D printing. The material under consideration is derived from PET plastic, a substance commonly employed in the manufacturing of beverage containers. It exhibits a balanced set of properties that lies between those of PLA and ABS. PET-G is highly regarded because to its exceptional strength, durability, and chemical resistance, making it a very suitable option for applications that need such characteristics [33]. PET-G demonstrates a tensile strength of around 59 MPa, an elongation at break of 6%, and a melting point ranging from 200 to 220 degrees Celsius. The appropriateness of the material for 3D printing may be due to its well-balanced mix of qualities, including durability and flexibility. According to the literature, PET-G has exceptional layer adhesion, hence minimizing the occurrence of delamination [34]. Researchers have shown interest in the field of PET-G composites. A study examining the impact of integrating different additives, such as carbon nanotubes and nanoclay, into PET-G matrices may provide valuable insights into the improvement of its mechanical, thermal, and electrical characteristics. These composite materials may find use in sectors where precise performance attributes are of utmost importance [35].

2.3. Key properties and advantages of materials

Table 1 provides a comparative overview of the main qualities and benefits of PLA, ABS, and PET-G materials often used in the context of FDM 3D printing.

Table 1. The fundamental characteristics and benefits associated with PLA, ABS, and PET-G materials

Material	*Tensile Strength (MPa)*	*Elongation at Break (%)*	*glass transition / melting temperature (°C)*	*Key Advantages*
PLA	*73*	*5*	*60 / 175*	*Biodegradability, ease of use, aesthetic finish*
ABS	*27*	*30*	*105 / 220-250*	*Durability, impact resistance, heat resistance*
PET-G	*59*	*6*	*85 / 200-220*	*Balance of durability and flexibility, chemical resistance*

3 Research methodology

In order to carry out this complete study, a thorough examination of the existing literature was conducted by searching several web databases such as PubMed, Google Scholar, ScienceDirect, IEEE Xplore, and ResearchGate. The search phrases included in this study encompassed "Fused Deposition Modeling," often referred to as "FDM," as well as "3D Printing," "PLA," "ABS," "PET-G," and "Thermoplastic Polymer." These terms were used individually and in various combinations. The inclusion criteria included peer-reviewed journal articles, conference papers, patents, and books. The selected research articles for this study were limited to those published within the last decade. The data in this study predominantly concerned the materials used, the printing technique applied, any additives included, and the subsequent impact of these factors on material qualities. The objective behind this information categorization was to establish a thorough comprehension of the materials and their potential for improvement in FDM 3D printing applications. An extensive analysis was conducted to juxtapose the study results, with a focus on the merits and drawbacks of each material, as well as the identification of new avenues for future research.

4 Effects of additives on material properties

4.1. Effects of additives on PLA

The focus of academic investigation has been on the inclusion of additives to heighten the mechanical, thermal, and electrical characteristics of PLA, ABS, and PET-G. A plethora of research inquiries have been dedicated to the examination of the effects of additives on the material properties used in FDM 3D printing, leading to enhancements in performance attributes and an expansion of the range of potential applications for such materials (see Figure 5). Scrutiny of PLA-graphite composites has been carried out in an endeavor to elevate the mechanical, thermal, and electrical characteristics of PLA. As per the research conducted by Stefano et al. (2022), the inclusion of graphite was found to have engendered an increase in both the glass transition temperature and degree of crystallization of the material. A role was assumed by graphite as a nucleating agent in promoting crystallization during the cooling phase. The potential for improvement in mechanical and thermal attributes of PLA through the utilization of specific additives was observed [22].

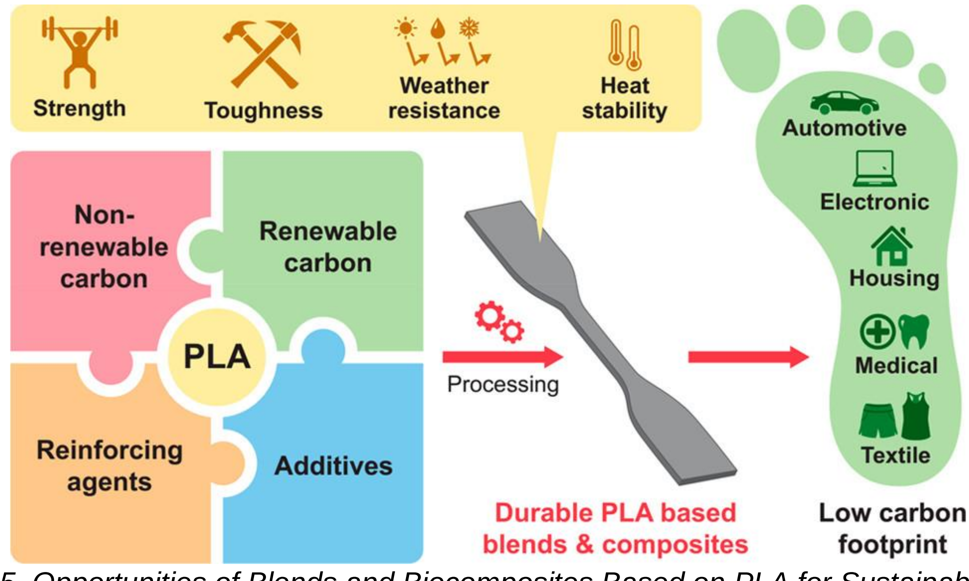

Figure 5. Opportunities of Blends and Biocomposites Based on PLA for Sustainability [36]

Cellulose, a natural biopolymer, has been under exploration as a potential constituent for composites containing PLA. The idea that the inclusion of cellulose in PLA led to enhancements in both mechanical and thermal attributes was supported by research conducted by Kumar et al. (2020). An increase in tensile strength and thermal stability was observed in PLA-cellulose composites, rendering them suitable for scenarios necessitating heightened mechanical attributes and elevated resistance to elevated temperatures. The potential to broaden the scope of applications for materials based on PLA was indicated by the research results [26].

Further scrutiny has been applied to additives, beyond graphite and cellulose, to assess their impact on the attributes of PLA. Research undertaken by Elhattab et al. (2021) centered on the examination of amorphous magnesium phosphate (AMP) as an additive in PLA composites. According to research, the inclusion of AMP resulted in the enhancement of the material's flame-retardant attributes, holding promise for potential use in various sectors such as the electronics and construction industries [21]. The topic of scientific inquiry has also encompassed the use of carbon nanotubes (CNTs) as an additive for PLA. The capability of carbon nanotubes (CNTs) to improve both electrical conductivity and mechanical attributes has been explored. The impact of carbon nanotubes (CNTs) on PLA was examined by Spinelli et al. (2019), and it was observed that the incorporation of CNTs resulted in enhanced electrical conductivity without compromising favorable mechanical attributes. Opportunities for potential applications in the domains of conductive polymers and electronics are presented by this study [37].

The exploration of the incorporation of graphene into PLA has been conducted by several researchers. The potential role of graphene, renowned for its exceptional electrical conductivity and mechanical attributes, has been considered. The potential to yield composites with improved mechanical strength, thermal conductivity, and electrical conductivity is offered by the use of graphene in PLA. The application of graphene-PLA composites holds promising prospects in multiple fields, encompassing sensor technology, battery development, and the manufacture of 3D-printed electrical devices [38].

4.2. Effects of additives on ABS

The notable attributes of strength, impact resistance, and durability are well recognized in ABS material. Nevertheless, advantages may be conferred upon it by the addition of additives in augmenting its mechanical, thermal, and electrical qualities. The scope of ABS material research has been broadened beyond the incorporation of additives, including the exploration of optimization of 3D printing conditions for the purpose of mechanical characteristics regulation. The study conducted by Abeykoon et al. (2020) examined the impact of several printing factors, including layer orientation, infill density, and printing speed, on the tensile characteristics of ABS. The considerable influence of these variables on the tensile strength of the material was underscored by the findings. A fundamental basis for future investigations seeking the customization of the mechanical characteristics of ABS components by considering particular printing settings is established by the presented study [39]. Extensive research on the incorporation of graphene into ABS has been conducted to augment its mechanical and thermal characteristics. ABS copolymers greatly influences the physical and chemical properties of the plastic. Because it can be rubbery, crystalline, glassy, etc., according to the proportion of its constituents. In general, ABS is a strong plastic, flexible, breaks less, has a softer surface than other plastics, can be sanded and machined easily, making it ideal for prototyping. The tensile strength and Young's modulus can be further increased by adding graphene oxide (2% GO) [40].

4.3. Effects of additives on PET-G

PET-G is a versatile material that exhibits a wide range of characteristics, making it suitable for the 3D printing process. Numerous investigations have been undertaken to examine the impact of additives on PET-G, with the objective of augmenting its mechanical, thermal, and electrical properties. In 2022, Vijayasankar K. et al. explored PETG-based composites for biomedical applications, emphasizing their biocompatibility, formability, thermomechanical stability, and wear resistance. They used silk as a filler, produced various composite fibers with different silk content, developed a 3D printing protocol, and found that 2% silk-PETG had the best properties. Additionally, they printed a lower limb prosthetic socket [41]. In 2023, Alarifi investigated FDM printed PET-G/carbon fiber, revealing significantly lower wear rates in slow-speed dry sliding contact, especially in pin-on-disc testing. This wear resistance is an order of magnitude better than existing literature. Annealing reduced wear further, while nitrogen atmosphere production increased it, with oxidation observed through X-ray photoelectron spectroscopy during FDM printing [42].

A research by Ferreira et al. (2019) demonstrated that the introduction of nanoclay had a beneficial effect on the mechanical attributes of PET-G, specifically regarding tensile strength and modulus.This enhancement positions PET-G as a plausible material for a broad spectrum of applications that demand superior mechanical properties [43]. Beyond carbon nanotubes and nanoclay, additional additives have been investigated in PET-G composites, including nanoscale fillers and flame retardants. The potential to exert a considerable impact on the material's mechanical, thermal, and electrical characteristics is held by the utilization of these substances. A dynamic and evolving field of research is represented by the exploration of additives in PET-G materials, providing numerous prospects for customization to meet specific performance criteria.

4.4. Summary of results

The worldwide adoption of Fused Deposition Modeling (FDM) 3D printing has been contributed to by its accessibility and adaptability. The determination of the performance, qualities, and potential uses of the produced items is carried out by the materials selected in FDM 3D printing. Commonly used materials for FDM in 3D printing include PLA, ABS, and PET-G. Their properties, encompassing mechanical, thermal, and electrical features, were investigated, and the potential for enhancement through additives was explored. PLA is recognized for its biodegradability and versatility across applications, owing to its user-friendly and eco-conscious characteristics. Investigation into the incorporation of additives, such as graphite, cellulose, and amorphous magnesium phosphate (AMP), was conducted to improve the mechanical, thermal, and electrical characteristics of the material. The capacity of these additives to expand the scope of PLA applications, especially in domains where biodegradability and improved performance are crucial, was demonstrated. The potential for enhancing its use across diverse industrial sectors exists through additional investigation into the optimization of the composition and concentration of additives, as well as their impact on the characteristics of PLA.

Strong and resilient nature, as well as the capacity to withstand impact and endure over time, are notable characteristics of ABS material. Applications that require such capabilities, including the production of functioning prototypes and automobile components, find ABS well-suited. Superior heat resistance in comparison to PLA is one of the primary advantages of ABS. The scope of research has expanded to include the optimization of parameters in 3D printing processes, as well as the use of graphene as an additive to enhance the characteristics of ABS materials. The potential to augment both tensile strength and thermal conductivity has been shown in the use of graphene as an additive. Continuing to be highly esteemed as a sought-after material in sectors requiring robust and thermally resilient components is ABS.

Renowned for its capacity to offer a harmonious combination of durability and flexibility, accompanied by exceptional resistance to various chemical substances, is PET-G. Versatility is exhibited by this material, finding usage in various industries, including the manufacture of mechanical components, food packaging, and medical apparatus. The investigation of researchers into the effects of incorporating carbon nanotubes (CNTs) and nanoclay as additives in PET-G for the purpose of enhancing its electrical and mechanical characteristics has been undertaken. The promise of expanding the use of PET-G in multiple fields, such as conductive polymers, electronic devices, and applications necessitating improved mechanical qualities, is held by the inclusion of these additives.

4.5. Potential research possibilities

The prioritization of the refinement of the characteristics of PLA, ABS, and PET-G through the utilization of sophisticated additives and innovative composite compositions should be made in future research in the field of FDM 3D printing materials. There are several potential research possibilities that may be explored:

- Biodegradable composites, particularly those composed of PLA and combining natural additives, provide a viable ecologically conscious alternative. Further research may be conducted to explore the compatibility of PLA with other biodegradable materials, as well as the potential for changing current additives, in order to enhance its qualities.

- Further investigation may be conducted to study the incorporation of advanced additives, in addition to graphene, into ABS in order to get enhanced mechanical, thermal, and electrical characteristics. Another intriguing line of research is the production of ABS composites that are customized for particular industrial purposes.

- The customisation of PET-G composites for many applications, including but not limited to medical devices, electronics, and automotive components, has significant prospects. The exploration of innovative additions and the optimization of their concentrations are of utmost importance.

- Exploring the Viability of Recyclable Materials for 3D Printing: An Examination of Materials that Simultaneously Promote Sustainability in the Industry.

- The integration of FDM with cutting-edge manufacturing technologies, such as nanotechnology and 4D printing, has the potential to facilitate the creation of intelligent materials and structures.

- The investigation of multi-material and multi-process 3D printing technologies has the potential to facilitate the fabrication of intricate and utilitarian items with a wide range of features within a single printing process.

- In-Process Monitoring: It could be the objective of a possible future study is to explore the advancement of in-process monitoring and feedback systems in the context of 3D printing. The primary aim is to establish mechanisms that can effectively ascertain the quality and consistency of printed items during the printing process.

- Examination of the use of FDM materials in the realm of personalized medicine, including patient-specific implants and prosthetics within the medical and healthcare sector. - Analysis of techniques aimed at recycling and repurposing 3D-printed materials, therefore fostering sustainability and promoting the principles of a circular economy.

5 Conclusion

The advent of Fused Deposition Modeling (FDM) 3D printing has brought about a significant transformation in the processes of item design, prototyping, and manufacturing. The careful choice of materials in FDM 3D printing is of paramount importance as it significantly influences the performance and suitability of the produced products for various applications. PLA, ABS, and PET-G are widely favored options, each presenting distinctive characteristics and benefits. Scholars have conducted investigations into the integration of diverse additives with the aim of augmenting the mechanical, thermal, and electrical characteristics of these materials, hence broadening their potential uses. The additive manufacturing business is in a state of constant evolution, characterized by the ongoing development of novel materials, additives, and printing methods. The advancement of research in this particular domain holds significant promise for the development of tailored, high-performance materials and the exploration of novel applications across several sectors. The future of FDM 3D printing materials and their uses will be influenced by a collaborative endeavor towards sustainability, as well as breakthroughs in the field of material science.

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