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Reviewing the Use of Extrusion Technology in Additive Manufacturing for Polymer Composites

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ABSTRACT:

Additive manufacturing (AM) makes it possible to create intricate cellular structures and other three-dimensional things through the use of extrusion. This is accomplished by depositing the material in discrete layers at various scales (macroscopic, mesoscopic, and microscopic) through a nozzle or orifice. Because of their widespread use and potential applications in fields including healthcare, military, aerospace, and transportation, polymers and their composites have attracted a lot of attention in the field of AM. The primary focus of this study is on the use of extrusion-based AM methods for the structural fabrication of architecture polymer-based structures. When compared to their bulk analogues, these structures have superior material properties such as low density and good mechanical performance. In this introductory piece, we will examine the AM methods that rely on extrusion and the wide variety of materials, architectural shapes, and mechanical properties that may be achieved by extrusion printing. In this work, we explore some potential future applications made possible by recent developments in polymer and composite materials. In order to enhance the development of lightweight, high-performance materials formed from polymers and their composites, the study provides a series of recommendations for further investigations in the field of extrusion-based AM.

Keywords: Polymer composite, Extrusion technology, AM, Composite materials

1. Introduction:

There is now a contentious discussion taking place within academic and corporate circles around AM, as it is often seen as the fifth industrial revolution (Borandeh, et al., 2021). There is a dearth of academic research in the domains of AM and 3D printing, with a restricted body of knowledge including AM and its corresponding findings (Chatham, et al., 2019). In order to ensure a successful future for AM materials, it is imperative to incorporate parallel processes and technologies. In recent years, there have been notable advancements in the field of AM and four- and five-dimensional printing, which have garnered considerable attention (Justo, et al., 2018).

Tissue engineering and other therapeutic applications using AM technology show great promise. And because AM makes it possible to create tailor-made drug delivery systems, patients can choose from a wide variety of formulations that differ in size, colour, taste, and shape all of which have been shown to improve medication adherence (Justo, et al., 2018). The direct printing of complex structures has been the primary focus of recent AM research. More and more people are curious about how they may utilise AM to create “multiples,” tablets that release multiple pharmaceuticals all at once and are made using a combination of Fused Deposition Modelling (FDM) and injection moulding (Islam, et al., 2018). Changing these structures is an easy method of creating an appropriate release profile, one that takes into account the medicine's unique properties and the patient's or environments physiological and environmental conditions (Das, et al. 2020).

AM techniques, also referred to as 3D printing, have emerged as a potential solution to tackle these challenges due to their ability to provide precise control and adaptability in fabricating intricate designs with high resolution, specifically for structural applications (Justo, et al., 2018). Polymers find extensive utilisation across diverse sectors such as transportation, aerospace, medical, and electronics, rendering them highly sought-after as a class of structural materials (Habib, et al., 2017).

Various methods of AM, including binder jetting, sheet lamination, powder bed fusion, direct ink writing (DIW), and fused filament fabrication (FFF), are commonly employed in the manufacture of polymer-based components (Islam, et al., 2018). Both of these techniques can be classified as extruder-free printing technologies. Non-extrusion-based techniques have several limitations in comparison to their extrusion-based counterparts (Lewicki, et al., 2017). These factors encompass a reduced selection of print medium options, increased costs of materials, and more complex calibration processes. The utilisation of extrusion-based printing techniques holds considerable potential for the advancement of materials and their structural applications (Kuhnt, and Camarero-Espinosa, 2021).

1.1 Applications of FDM base polymers and composites:

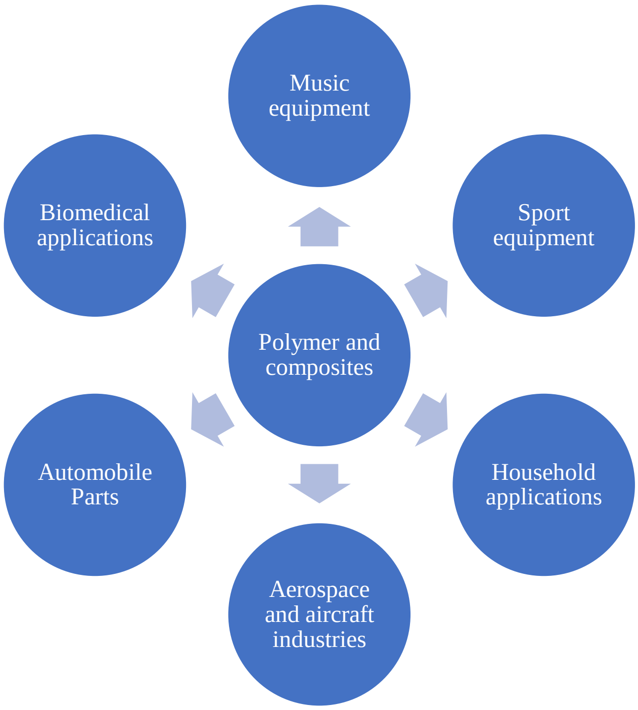

Figure.1. Applications of FDM-based polymers (Source: Author)

The production of polymer-based fibre composites using FDM has increased in popularity in recent years. After fibre was added to the thermoplastic matrix, the material's modulus, tensile strength, and bending strength all increased. This development broadens the potential applications of FDM-printed materials in structural settings (Ligon, et al., 2017).

The failure probability of polymers and composites is raised by manufacturing uncertainties introduced by FDM, such as the emergence of holes and flaws and the lack of layer bonding (Patel, and Taufik, 2022). While FDM has several advantages, the durability and dependability of materials are still heavily dependent on how well they function under assessment. The effectiveness of FDM components is affected by a number of factors, some of which will be discussed below (Nouri, et al., 2021).

There are a variety of factors that influence the end product, including printing parameters, bonding characteristics, material composition and reinforcing, and defects in the FDM process. Including these elements increases the mechanical strength of 3D printed fibre composites significantly (Patel, and Taufik, 2022).

2. Polymer based composite materials:

Polymers have been extensively and effectively utilised for both Fused Filament Fabrication (FFF) and DIW due to its advantageous characteristics such as light weight, affordability, high modulus-to-weight ratio, corrosion resistance, and possible electrical and mechanical properties (Patil, et al., 2017). Prominent thermoplastic materials that belong to the family of FFF encompass acrylonitrile-butadiene-styrene copolymers (ABS), polylactide (PLA), polycarbonate (PC), and polyamides (PA). These materials are known for their tensile strengths, which typically span the range of 20-60 MPa. Thermoplastics can be categorised into two main groups: amorphous thermoplastics, such as ABS and PC, and semi-crystalline thermoplastics, such as PLA and PA (Rau, et al., 2018).

Due to their affordability, biocompatibility, reliability, and potential for scalability, these thermoplastics are experiencing a growing use. In this particular case, it can be argued that PLA exhibits superiority as a result of its comparatively low printing temperature and low coefficient of thermal expansion (Patel, and Taufik, 2022). According to empirical evidence, PLA has superior performance in terms of tensile strength and surface finish when compared to ABS (Rau, et al., 2018). Furthermore, it should be noted that in addition to the thermoplastics stated before, epoxy and other thermosets also possess the capability of being printed using the DIW method (Patil, et al., 2017).

Thermosetting polymers, such as epoxy, frequently exhibit superior strength in comparison to thermoplastic materials, mostly attributed to their densely interconnected molecular structure (Szymczyk, et al., 2020). The DIW technique exhibits a greater capacity for accommodating diverse substrates compared to the FFF method. This is primarily attributed to DIW's reduced reliance on the inherent characteristics of the material being used, instead placing greater emphasis on the rheological qualities of the ink employed (Singh, et al., 2020). Although low-cost thermoplastics have several applications, it is widely acknowledged that they include performance limitations that may undermine the overall strength and longevity of the printed structure (Singh, et al., 2019). In the context of FFF and DIW, materials possessing a high level of mechanical strength are considered highly desirable (Rau, et al., 2018).

The challenge lies in meeting the growing demand from industry for outstanding performance thermoplastic like polyetheretherketone (PEEK) and poly-tetrafluoroethylene (PTFE) and high-performance thermosets like bismaleimide (BMI). This is primarily due to the higher cost of these components compared to commodity polymers (Singh, et al., 2019).

3. Method based on polymer composite:

In the extrusion-based additive manufacturing process, molten and semi-molten polymers, pastes, solutions, and dispersions are sequentially deposited in layers (Singh, et al., 2019). This deposition is facilitated by a mobile nozzle or aperture known as an extrusion print head. Two commonly used extrusion-based printing processes in the field are FFF and DIW. Due to their cost-effectiveness, rapid production capabilities, and minimal material wastage, these methodologies have garnered significant attention (Tamburrino, et al., 2021).

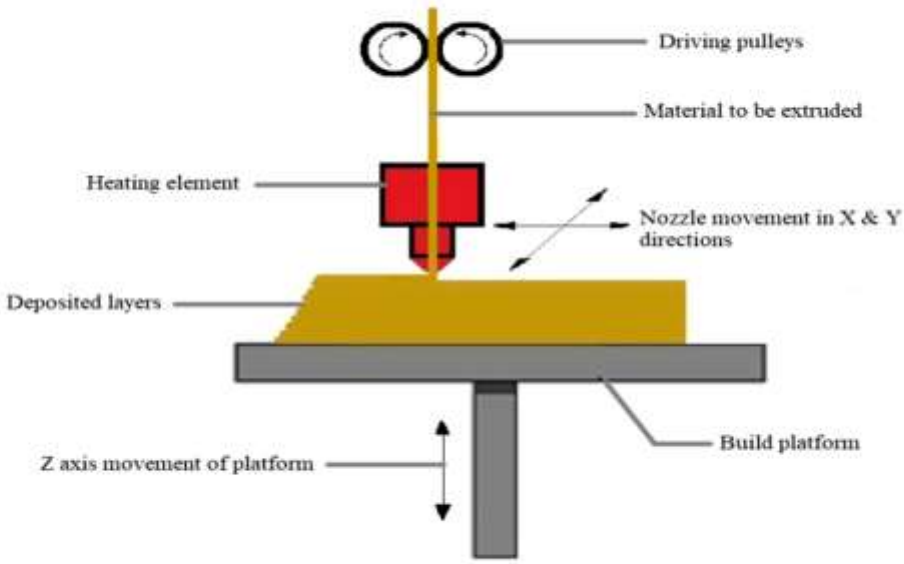

Figure.2. Schematic diagram of extrusion based AM (Source: Tan, et al., (2020))

The business strata-sys is widely acknowledged as the pioneering entity responsible for the development and patenting of the additive manufacturing process referred to as Material Extrusion (Tamburrino, et al., 2021). The utilisation of this particular approach played a pivotal role in the advancement of the consumer 3D printing sector and the extensive acceptance of additive manufacturing within the industrial domain, prior to the expiration of its patent in 2009 (Utekar, et al., 2021).

As previously stated, filament-based 3D printers utilise thermoplastic polymer filament. The extruder head, with its vertical and rotational movements, retrieves the printer's filament from a spool (Wu, et al., 2020). The head of the extruder is instructed to apply material in progressively thinner layers along a predetermined tool path that aligns with the cross-sectional boundaries of the component (Wang, et al., 2017). To achieve the fabrication of a structurally sound three-dimensional object, the bed undergoes a downward displacement equivalent to the thickness of each individual layer, while the nozzle consistently deposits semi-molten material within pre-established boundaries (Utekar, et al., 2021).

SLA and DLP techniques provide remarkable resolution and the ability to construct intricate structures, rendering them very suitable for scaffold fabrication. Additionally, the ease with which scaffold characteristics can be modified by manipulating the liquid resin composition further enhances their suitability for this purpose (Patel, and Taufik, 2022). The PLA/Iron scaffold exhibited significant promise for utilisation within the context of bone tissue production (Szymczyk, et al., 2020). In the future, it may be possible to utilise 3D printing technology for the fabrication of polymer-based composite scaffolds, provided that a more comprehensive understanding of the interplay between fabrication techniques, thermal behaviour, and structural characteristics is achieved (Tamburrino, et al., 2021). Additionally, the simulated body will undergo on-going monitoring to detect any instances of mechanical integrity failure (Wang, et al., 2017).

The use of FDM during production has reduced porosity. This study intends to advance the field of bone tissue engineering by developing PLA scaffolds with enhanced mechanical properties. Changing construction orientation, layer thickness, and feed rate can affect the PLA parts' anisotropic mechanical characteristics, as reported by Nouri, et al., (2021). Tamburrino, et al., (2021) used FDM to create poly scaffolds for use in breast reconstruction surgery. Digital patient data was used to inform the scaffold's physical construction.

Various techniques, such as UV-induced polymerization, ink-jet printing, laser melting, and extrusion, are employed to fabricate the many layers. Historically, the first exploration of 3D printing predominantly revolved around polymers (Borandeh, et al., 2021). However, in recent times, there has been a notable resurgence of attention towards the utilisation of metals, ceramics, and composites in the printing process, with the aim of fabricating useful components (Balla, et al., 2019). Metallic objects possessing mechanical properties comparable to those of bulk metals can now be produced via the utilisation of AM methods that rely on high-power lasers and electron beams (Chatham, et al., 2019). The utilisation of AM enables the creation of intricate shapes using a wide range of materials, a capability that is not achievable using conventional production techniques. The current availability of materials is constrained due to the specific requirements of distinct additive manufacturing techniques (Kuhnt, and Camarero-Espinosa, 2021).

4. Electronic applications:

FFF and DIW production techniques have been widely employed in several industries, largely for the purpose of expediting the prototype process and facilitating the manufacture of limited quantities (Borandeh, et al., 2021). The implementation of these AM techniques has the potential to decrease the overall cost associated with the design-to-manufacturing process (Chatham, et al., 2019). This is achieved by enhancing the manufacturability of intricate structures, hence simplifying their production. Recyclebots refer to a specific category of specialised FFF printers (Justo, et al., 2018).

These printers are capable of producing filaments for extrusion by first shredding recycled thermoplastics. The primary advantage of FFF printers lies in their ability to employ filaments derived from this waste material (Chatham, et al., 2019). According to our research, a distinct hierarchy may be observed in the relationship between AM processes and polymer-based industrial applications. In diverse domains such as transportation and medicine, there have been recent endeavours to employ 3D printing technology for the fabrication of polymers (Justo, et al., 2018).

One particular domain pertains to the enhancement of positioning and assembly jigs and fixtures. CNC machining is employed due to the imperative need for exceptional precision in its utilisation (Islam, et al., 2018). The need for extensive customization in jigs and fittings results in increased manufacturing time and cost (Lewicki, et al., 2017). The mechanical characteristics of scaffolds used in tissue engineering play a crucial role, particularly in applications that include bearing loads. Polymer-based scaffolds have been fortified with inorganic, organic, and carbon fillers and fibres to augment their mechanical properties for utilisation in biomedical applications (Patel, and Taufik, 2022).

5. Conclusion:

This concise overview aims to examine the latest research discoveries pertaining to AM of polymeric composites, along with its prospective applications. The subsequent content presents the findings derived from this initial inquiry. The four primary categories of 3D printing encompass liquid-based, filament-based, paste-based, powder-based, and solid sheet-based printing methods. The limitations of traditional AM polymers sometimes render them unsuitable for demanding applications.

The extended time required can be attributed in part to doubts about the consistency and reproducibility of additive manufacturing parts. The development of high-performance functional materials is crucial to the full promise of AM being realised. These objectives are made possible by the compatibility between AM technology and composite materials. A composite is the result of the combination of many materials. Polymer composites have been the subject of extensive research into the problem of material selection and the improvement of printed component features due to their exceptional mechanical capabilities in terms of strength and stiffness.

The incorporation of fibers/fillers into AM composites leads to enhancements in the mechanical properties of the material. The incorporation of fibres and fillers into polymers has been shown to enhance their functioning and properties. The preference for short, discontinuous fibres in AM arises from the challenges associated with handling longer, continuous fibres. In theory, AM has the potential to enable cost-effective large-scale manufacturing of fiber-reinforced composites. Most extrusion-based processes can be utilised to manufacture polymeric composites reinforced with short fibres.

Extrusion-based AM technology has the potential to achieve enhanced manufacturing efficiency and the capability to construct complicated polymeric structures. The continuous development of novel materials, such as resins, filaments, dyes, and intricate architectures inspired by nature, has significantly advanced these techniques, positioning them as leading practises in contemporary manufacturing. Multiple studies have demonstrated that the geometric characteristics of a design can exert a substantial influence on its mechanical performance. This phenomenon carries extensive ramifications throughout a wide range of disciplines, including but not limited to medicine, aeronautical engineering, and electronics.

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