Materials for Filament Fabrication

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Fused filament fabrication (FFF) is one of the most popular additive manufacturing (AM) processes that utilize thermoplastic polymers to produce three-dimensional (3D) geometry products. The FFF filament materials have a significant role in determining the properties of the final part produced, such as mechanical properties, surface quality, thermal conductivity, and electrical conductivity.

Keywords: additive manufacturing ; fused filament fabrication ; thermoplastics ; bioplastics ; composites

1. Overview

Fused filament fabrication (FFF) is one of the most popular additive manufacturing (AM) processes that utilize thermoplastic polymers to produce three-dimensional (3D) geometry products. The FFF filament materials have a significant role in determining the properties of the final part produced, such as mechanical properties, surface quality, thermal conductivity, and electrical conductivity. This article intensively reviews the state-of-the-art materials for FFF filaments. To date, there are many different types of FFF filament materials that have been developed. The filament materials range from pure thermoplastics to composites, bioplastics, and composites of bioplastics. Different types of reinforcements such as particles, fibers, and nanoparticles are incorporated into the composite filaments to improve the FFF build part properties. The performance, limitations, and opportunities of a specific type of FFF filament will be discussed. Additionally, the challenges and requirements for filament production from different materials will be evaluated. In addition, to provide a concise review of fundamental knowledge about the FFF filament, this article will also highlight potential research directions to stimulate future filament development. Finally, the importance and scopes of using bioplastics and their composites for developing eco-friendly filaments will be introduced.

2. Additive Manufacturing

Additive manufacturing (AM) processes can produce parts from different materials such as metals, ceramics, composites, and thermoplastics for applications in diverse fields, including aerospace, automobile, and health care [1][2][3]. Some known unique features of AM processes over conventional manufacturing processes are that the lighter weight parts can be achieved by adjusting infill density, and part production with complex geometries can be produced without costly tooling [4]. A complex-shaped part can be fabricated from a computer-aided design (CAD) model by any AM machine. This reduces machining requirements and space utilization since AM processes do not require jig, fixtures, tools, and molds like milling, injection molding, drilling, or broaching process [5]. Additionally, nonvalue-added activities such as workpiece loading and tool changing during the manufacturing operations are also reduced in AM. Manufacturing wastes such as material chips are minimized in AM processes. On the other hand, AM processes may generate other material waste such as support materials and lose powders. Although the AM processes have several advantages over the conventional manufacturing processes, the applications of AM build parts as functional products or components are limited [6].

The potential for AM processes is astounding, but their capacity is limited. There are several AM processes, and the AM processes are divided into seven major families according to the ASTM F2792-12A [7]. Commonly used technologies under each family are: (1) binder jetting: powder bed and inkjet head, (2) directed energy deposition: laser metal deposition (LMD), (3) material extrusion: fused filament fabrication (FFF), (4) material jetting: multi-jet modeling (MJM), (5) powder bed fusion: selective laser sintering (SLS), direct metal laser sintering (DMLS) and electron beam melting (EBM), (6) sheet lamination: laminated object manufacturing (LOM) and ultrasonic consolidation, and (7) vat photopolymerization: digital light processing (DLP) and stereolithography apparatus (SLA) [8]. Most commonly, the AM processes produce objects from CAD models by depositing layers upon layers. Compared to the consistency that can be achieved from commercial manufacturing processes, the parts produced by AM processes often fail to meet different functional requirements (mechanical, thermal, and electrical properties, thermal stability, dimensional accuracy, surface quality, or multiaxial load-bearing capacity).

The availability of raw materials for AM processes is another crucial factor that hinders AM processes from being employed on a large scale. In most AM processes, only certain types and forms of materials can be employed. Metals, polymers, ceramics, and composites are often used as raw materials in AM processes. The raw materials for AM also exist in various forms, such as powder, sheet, liquid, and filaments form. Among the AM raw materials, polymers are the most widely used material [9]. The scope of this paper will focus only on the materials for the FFF process.

Fused Filament Fabrication

The fused filament fabrication (FFF) process utilizes thermoplastics in the shape of filaments to produce prototypes and functional parts [10]. Although the FFF is considered a low-cost process among other AM processes, the applications of AM in the world's manufacturing efforts to produce functional parts are limited. This limitation is due to several reasons: poor part properties, limited raw materials, restricted part size, and low production rate. The properties of FFF build parts depend on process parameter selection, filament materials, filament properties, among other factors.

Process parameters optimization is one of the most popular research areas in the advancement of the FFF [11][12]. However, the part properties of an FFF build part can only be improved to a certain extent by determining an optimum combination of process parameters through process parameter analysis [13]. This is because the pure thermoplastic materials used for the FFF process also have inherent material properties boundaries that cannot be exceeded. Another limitation of process parameter analysis is that the optimum combination of process parameters is not generalized across all filament materials, built shapes, or equipment. An optimum combination of process parameters for a part property from one filament may not be optimum for another part properties or other filament materials [14]. For this, process parameter analysis by itself is not sufficient for meeting all functional requirements of many applications.

Along with the advancements in the process parameter analysis, it is crucial to continuously search for new filament materials that can be used to produce high-quality parts to expand application areas. In addition to pure thermoplastics as filament materials, composite materials, specifically polymer matrix composites, can be a viable option for filament preparations. Researchers and industrial experts have been researching to develop new composite materials for filaments by blending different reinforcements such as particles, nanoparticles, and fibers with thermoplastics. Composite materials are getting attention from researchers for FFF filaments due to their unique properties and low cost [15][16].

Several additional factors should be considered when developing composite filaments. Materials for FFF filaments need to meet several specific requirements: glass transition temperature, ductility, melting points, viscosity, crystallinity, or tensile properties to print parts with the FFF process. Moreover, the adhesion between polymer and reinforcement is another crucial factor for composite properties. The selection of matrix and reinforcement combinations is essential in developing composite filaments. The properties of composites parts depend on bonding between matrix and reinforcement and void content in composites. As the utilization of the FFF process will increase in the future, the new composite filament materials development should also focus on the environmental impacts of composite build parts. For composites filaments, either polymer matrix and reinforcements or both of them can be synthetic or natural. Environmentally friendly composite filaments can be prepared using natural reinforcements with biodegradable polymer matrix materials.

This paper focuses on systematically reviewing the available materials for the FFF filaments, including pure thermoplastic, composite, and bioplastic filaments. Although there are a few review papers on composites materials for the FFF process [17][18][19], to our best knowledge, very few of the published articles concentrated on the filament preparation process and bioplastic filament preparation challenges and opportunities. All the existing review papers are mainly focused on composites filament development and the properties of composite build FFF parts. Along with analyzing the available filament materials, this paper will cover the filament fabrication requirements and the difficulties, the material selection for FFF filament, and the future research direction for the development of composite filaments. Additionally, the scope, challenges, requirements for bioplastic and their composite filament development for the FFF process will be discussed.

3.Conclusions

One of the biggest challenges for adopting additive manufacturing as a commercial production method is the availability of suitable materials. The requirements such as mechanical properties, thermal conductivity, electrical conductivity for real-world applications may not be fulfilled by parts produced from pure thermoplastic filaments. It is essential to search for new filament materials to increase FFF applications in different fields. Polymer matrix composites as FFF filament can be a viable option for FFF printed functional parts. Many types of reinforcements such as particles, fibers, and nanoparticles can be used with thermoplastics to improve FFF build part properties such as surface roughness, dimensional accuracy, and mechanical properties in polymer matrix composites. Along with pure thermoplastics and composites, bioplastics and their composites can be used as eco-friendly filament options. Polymer matrix and its reinforcements, both or one of them, can be organic, natural, and bio-based. Bio-based matrices and reinforcements are getting attention from researchers and industrialists in recent years due to their low cost and environmentally friendly properties. In this paper, the existing research on FFF filament materials is summarized extensively. The research gaps on the advancement of the FFF process and FFF filament material are identified and discussed. This review paper aims to help researchers and practitioners whose area is related to the FFF filament material selection and development. By broadening the FFF materials availability and choice, the barriers to adopting the FFF process or other additive manufacturing processes in commercial industries can be minimized.

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