A Review of Fused Deposition Modeling Process: Parameter Optimization, Materials and Design

Elisaveta Doncheva, Jelena Djokikj, Ognen Tuteski, Bojana Hadjieva

***Abstract*—** In the past decade, additive manufacturing technology or 3D printing has been promoted as an efficient method for fabricating hybrid composite materials and structures with superior mechanical properties and complex shape and geometry. Fused deposition modeling (FDM) process is commonly used additive manufacturing technique for production of polymer products. Therefore, many studies and experiments are focused on investigating the possibilities for improving the obtained results on product properties as a key factor for expanding the spectrum of their application. This article provides an extensive review on recent research advances in FDM and reports on studies that cover the effects of process parameters, material and design of the product properties. The paper conclusions provide a clear up-to date information for optimum efficiency and enhancement of the mechanical properties of 3D printed samples and recommends further research work and investigations.

***Keywords*—** additive manufacturing, critical parameters, filament, print orientation,

I. Introduction

Fused deposition modeling (FDM) is a cutting-edge additive manufacturing technology that is offering many advantages. It is an affordable, simple and reliable technology used for modeling, prototyping and production applications. FDM can produce products and structures with various complex geometries in series with a small amount of waste and without additional costs for tools or molds [1]. The production of FDM parts can be broken up in three stages which include pre-processing, production and post-processing [2]. In the pre-processing stage, the specification of the filament material layers is defined by slicing of 3D computer-aided design (CAD) file that has been inserted into the working system. Each slice of data is converted by the software into machine code that determines the tool path for the machine to follow. The deposition of extruded and melted filament is the production stage. The material filament is precisely guided and pulled by a drive wheel into a nozzle that heats the material to the semiliquid phase, making the material suitable for layering. Thin layers of liquified raw material are extruded along the tool path, layer by layer until the part is completed. The filament thermo-plasticity plays important role in the process because it dictates the ability to create bonding between the layers. The bonding, filament orientation, thickness and width of the layers, are some of the processing parameters that are crucial for the quality of the product in terms of their properties [1],[3]. The layers are deposited by moving down, following the thickness of the layer and the subsequent layers are built in the same way. In order to build complex shaped parts FDM uses support material apart from the build material which supports the overhanging structures during the process and helps in maintaining structural integrity [3]. Therefore, post-processing stage will include removing the supporting material and some finishing operations.

In order to meet the complex requirements of FDM process an advance in development of the material filament is a necessity. In the last decade, a well-recognized material for FDM production was the polymer, due to its ability to provide economic and structural benefits. Commonly used materials are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) [1]. Other materials used in FDM processing include polycaprolactone (PCL), polypropylene (PP), polyethylene (PE), polybutylene terephthalate (PBT), wood, nylon, metals, carbon fiber, graphene-doped PLA, etc. [1]-[3],[5]. There are also several other types of filaments that are currently being developed and introduced as commercial filaments [1],[4]. Combining various materials in order to overcome the lack of mechanical strength and functionality is a big challenge and the right road toward mechanical, thermal and durability improvement so that the composites can be considered the reference materials for the twenty-first century [7]-[8]. The filament composition and the optimization of process parameters are subjects of great interest for many researchers. The studies showed that different combinations of parameters show different results and that filament composition is not the only factor that influences them [9]–[11].

The scientific community is trying to understand the influence of the specific parameters on the FDM process and the quality of the product, but the interactions among these parameters are complex and require multi-objective approaches [5],[6]. Understanding the FDM process, filler materials, critical parameters and FDM design is an optimal solution for identifying the influential factors that can be modified,

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optimized or combined for obtaining products with perfect properties for a particular application. This study aims to provide an extensive overview of the various factors that influence the quality of FDM products. In the subsequent subtopics, the basic concept of FDM process and filament material production and types are highlighted. The optimization of critical printing parameters and quality aspects of the process are discussed and summarized. In addition, this study provides information on the most recent advances and recommendations on FDM design.

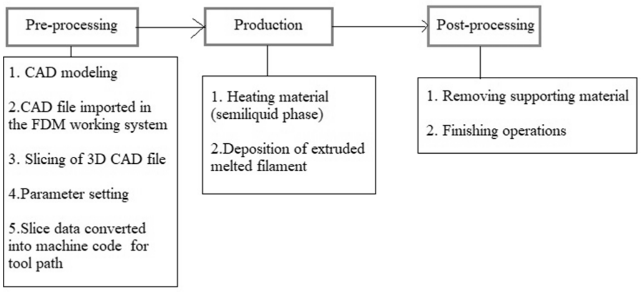

Fig.1 Stages of FDM product processing

II. FUSED DEPOSITION MODELING PROCESS

The FDM process often referred to as fused filament fabrication (FFF) process or material extrusion additive manufacturing technique, works on the additive principle by laying down layers that are extruded from the nozzle. As outlined in section I of this paper, the process can be divided into three main stages that follow one after another: pre-processing, production and post-processing. In the pre-processing stage, a CAD model of the desired product is developed. The CAD model is exported as a stereolithography (STL) file which is then sliced in a slicing software or the interface platform between the machine and computer [3]. The slicer software proposes settings to control the fraction of material and the infill pattern geometry, which can be optimized to reduce weight while maintaining good mechanical performances [11]. The basic principle that drives nearly all additive manufacturing machines is the creation of the virtual solid model, then breaking down this model data into a series of two-dimensional cross-sections and transferring these broken data to the machine [10]. This data is read by the FDM machine and used for calculation of the extruding path of the material so it can be placed layer by layer and develop the physical part. The second stage is the production of the FDM part. The filament material is drawn from a filament spool with a pair of rollers and directed towards the extruder which heats the filament to a semi-molten state. A basic illustration of the FDM process is presented in Fig.2.

The filament is continuously fed through the extruder and nozzle of the machine. The nozzle can move in three degrees of freedom, back and forth according to the coordinates of the original model until the FDM part is built. When finishing a layer, the base moves down the Z-axis and the next layer of 2D material begins to be applied on top. The mechanical systems and software used to control the nozzle temperature, speed and direction are very important and must work together in order to create a complex physical object with good quality. The semi-molten state of the filament allows the fusion of the layers. The bonding quality among polymer filaments in the fused deposition modeling process determines the integrity and mechanical properties of resultant prototypes [12]-[13]. Some products have overhangs and require support structures during the FDM process. Alternatively, some printers use a second nozzle utilizing a different material to print the support structure concurrently with the main component [9]. In the post-processing stage, the support structure is removed once the FDM product is complete.

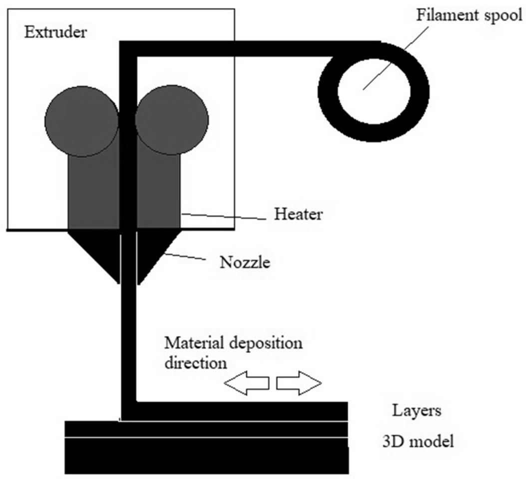

Fig.2 Schematic representation of FDM process

III. FILAMENT MATERIAL PRODUCTION AND TYPES

The quality of FDM products depends on three general factors: the operative performance and work quality of the machine, the continuity of material flaw and the quality of the filament that is used. Several studies have recently been performed to increase the range of materials available for FDM production, involving the optimization of process parameters and the use of different and sometimes uncommon materials [19]. This resulted in the utilization of FDM methodology in various manufacturing sectors. In order to understand the properties and behavior of FDM products, investigations and research should also be directed toward material filament composition. In this section, the production of the predominantly used filament materials is presented and all of the existing materials used as filaments are summarized and analyzed.

The commonly used filament materials for FDM manufacturing are polymers [1] and mixtures of different thermoplastic materials that generally have low or medium melting temperatures [14]-[17]. Polymer materials are commercially more popular for application, but the parts produced with this type of filament lack sufficient mechanical properties that are essential for various industrial applications and functional components. However, the mechanical properties of the polymer filament can be improved with a wide range of existing composite reinforcements [16].

The filaments produced from pure polymers can be directly used as FDM material, whereas the production of composite filaments is more complex because the characteristics of the material will strongly depend on the added reinforcement. Polymer filaments can be produced with the extrusion of raw polymer material through the holes of the extruder. The production of polymer composite filaments begins with preparing the mixture of the material before the extrusion process. This can be done with different mixing methods (solution, dry mixing, and others).

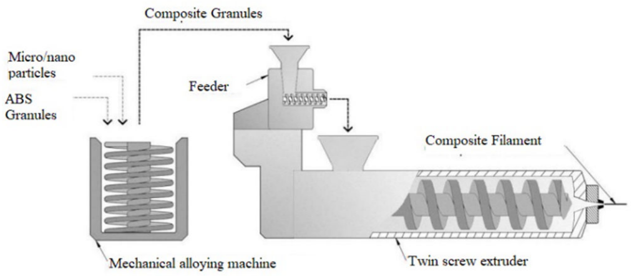

Fig.3 Production steps using mechanical mixer [25]

Fig.3 illustrates the production steps of composites with mechanical mixing [25]. The first step of the procedure is mixing the reinforcement particles with granules of acrylonitrile butadiene styrene (ABS) polymer with a mechanical alloying mixer for 10 minutes. The composite granules are later poured into the feeder part of the extruder for constant feeding. The speed of the feeder and the twin-screw are set to 15rpm and 73 rpm [25]. The barrel has 6 heating zones for obtaining extrusion temperatures from 175ºC то 210ºC. At the end of the barrel, there is a 2 mm wide hole for the exit of the pressured material [25]. After passing through the die, the extruded materials pass through a cooling zone where the quality of filament is significantly affected by the rate of colling [27]. The colling techniques that are commonly used for filaments are water bath and cold air gun. With the drawing process, the cross□section of filament can be reduced additionally after colling. During the extrusion process, die temperature, roller puller speed, spindle speed, inlet temperature, nozzle die and screw shape affects the filament diameter, the viscosity of the material and the direction of the filler in the filament.

The filament materials used in the FDM process are summarized in Fig.4 [19] and Fig.5 [26]. The categories used by the author in reference [19] is dividing the materials into commonly used and sustainable materials. Under the "commonly used" group, there are several polymers and composites and under "sustainable materials", there is a group of natural and recycled materials. In Fig.5 the author introduces the bioplastic group of filament material in addition to the commonly used group [26]. Biobased and biodegradable composites are the focus of many researchers due to their renewability, CO2 neutrality, and lower cost [20]. Biobased resources can accelerate the independence from non-renewable fossil fuel resources and biodegradability makes the product more valuable because it's minimizing environmental pollution [21]-[23].

There are also novel materials or additive materials that are specially intended for unique property applications with high performance. These are customized prototype filament materials with specially tailored properties that are a result of incorporated additives (nanomaterials, flame-resistant additives, metal particles, foaming filament, and others) in a thermoplastic feedstock matrix [23]. The introduction of unique additives can significantly influence occupational and environmental emissions and exposure potential, therefore quick and effective preliminary emission assessment of incorporated additives before mass production of parts is highly recommended for environment safety optimization [23][24].

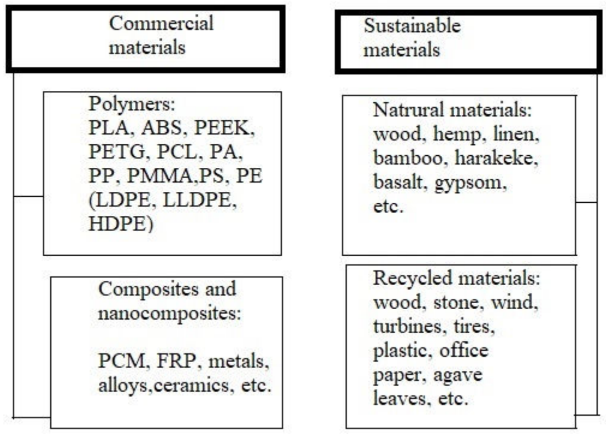

Fig.4 Overview of filament material used in FDM process [19]

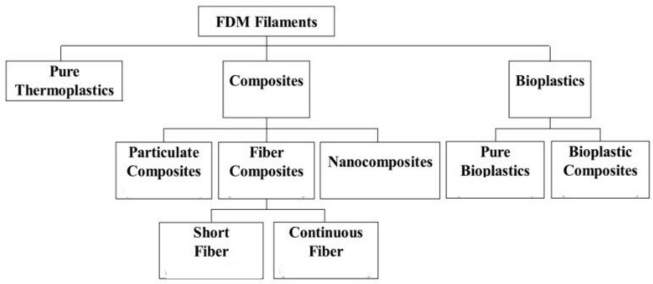

Fig.5 Overview of filament material used in FDM process [27]

The FDM filaments that are commercially available and their brief descriptions are summarized as follows:

ABS is an amorphous polymer that is widely used for manufacturing FDM parts [19]. In a molten state, this material shows good viscoelastic, thermal and rheological properties that allow easy processing via FDM [26]. It is an amorphous thermoplastic polymer made of petroleum that makes this material mediumly toxic and not biodegradable. ABS has high impact resistance, toughness, abrasion resistance, and chemical resistance that makes it suitable for application in the industry [28]. Has poor weather resistance due to olefinic bonds present in the butadiene core which is susceptible to UV degradation and this causes a decrease in the mechanical properties and yellowing of the material [27]-[28]. However, some disadvantages are present with ABS, such as shrinkage and warps before and after part production [27],[29]-[30]. ABS may produce chemical fumes that affect those with chemical sensitivities or breathing difficulties [26],[31].

PLA (polylactic acid) is a bio-based, biodegradable and biocompatible thermoplastic [19] with low thermal conductivity and toughness. The most important disadvantage is great sensitivity on temperature, which induces the degradation of the macromolecular structure [19] and humidity sensitivity over 60^0C [26]. PLA can be developed in medical applications because of its biocompatibility which is not metabolically harmful [1],[32]-[33]. This process can be achieved by turning PLA into a filament and then processing it through the FDM method. The filament can then be converted into various forms commonly used as implants [1]. The 3D printing scaffolding technique of FDM made a recent development of a PLA/graphene oxide (GO) nanocomposite material with a customized structure and it showed promising mechanical properties and cytocompatibility [1]. The tensile and flexural modulus is increased in e-glass fiber-reinforced materials [1].

PC (polycarbonate) material is an amorphous transparent thermoplastic polymer known for its strong mechanical properties, high glass transition temperature, and transparency [26]. It has high impact strength, dimensional stability and good electrical properties. On the other hand, polycarbonates are susceptible to humidity and have high print temperatures [26]. PC can print functional prototypes and has been employed in the automotive and aerospace industries [34]. It is well-known and widely used in industry for its versatile characteristics, eco-friendly processing and recyclability. PC material is lightweight and can be used for products that need to block ultraviolet radiation. Has good heat and chemical resistance. It is mostly used in the automotive and electronics industry.

PEEK (polyether ether ketone) is a technical thermoplastic with high mechanical and thermal performance [27] which makes it suitable for engineering applications. The process temperature of PEEK is high, around 340 °C [35], which is why it is considered a ceramic filler with a high melting temperature. It has good chemical resistance properties, excellent dielectric properties with low loss, good radiation resistance, solvent, wear and abrasion-resistant. Unfortunately, this material is not biodegradable. PEEK material has excellent fatigue properties, stress-crack, oxidation and acid resistance. The flexural strength and the fractural strain were significantly affected by the printing speed and by the infill percentage, respectively [36],[37]. It is used for the manufacture of aerospace components, as well as for medical support for the regeneration of human bone tissues [38]-[40].

PEI (Polyetherimide) is a high-performance lightweight thermoplastic, which possesses a high glass transition temperature (T_g), excellent flame retardancy, heat and smoke resistance and good mechanical properties [19][41]. It is a biocompatible polymer that has potential in fluoropolymer coating applications, but it has not yet had a large impact in major commercial coatings [19],[26],[42]. FDM parts produced from PEI have a poor surface finish and poor dimensional accuracy [37]. It is an amorphous, transparent, and amber thermoplastic with characteristics similar to PEEK [42]. In comparison with PEEK, it is less temperature resistant, less expensive and has lower impact strength. When subjected to chlorinated solvents, aromatic hydrocarbons or acetates, stress cracking can occur. Polyetherimide (PEI) is used in high-performance applications like automotive, aerospace, industrial and many more.

Nylon is a synthetic plastic polyamide known for its impressive mechanical properties (high strength weight ratio) impact and heat resistance and flexibility [26]. It is durable, inexpensive and has good toughness values as well [19]. Has low friction and good corrosion resistance. However, as hygroscopic material, it absorbs moisture extensively, reducing overall quality [39] and is prone to warping. Nylon is a widely used material for friction parts, prostheses and other machine elements. It is also used in the electronic industry as a nonconductive heat-resistant material [43].

HIPS (High impact polystyrene) is a biodegradable polymer, with good flow, impact and machining characteristics, high dimensional stability with low strength and cost [19]. It is obtained as a result of the free-radical polymerization of styrene in the presence of rubbers, usually polybutadiene (PB), for the improvement of mechanical properties [44]. The major disadvantages of using this material are poor wear resistance and it requires a high printing temperature and heated build platform [19],[44]. HIPS is preferred as a support material as it dissolves with chemicals such as limonene [19].

Other polymeric materials used as FDM material filaments are: polypropylene (PP), polymethyl methacrylate (PMMA), polystyrene (PS), types of polyethylene (PE), including low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), and polyethylene terephthalate (PET) [19]. Also, there are different combinations and mixtures of polymers that are for specific uses [19].

However, most of the parts manufactured using these materials lack sufficient mechanical strength and robustness to withstand mechanical loading for most of the functional mechanical components. This is placing obvious limitations and restricts the implementation of the FDM technology significantly. Therefore, developing novel materials with enhanced mechanical properties will help overcome these application obstacles. Polymer nanocomposites stand out as a potential solution to overcome this limitation because of having a larger surface area over a given volume by the transition of the dimension scale from micrometer to nanometer, nanometer scaled particles improve mechanical and physical properties significantly of the polymer materials [17][18].

IV. OPTIMIZATION OF FDM PROCESS PARAMETERS AND DESIGN CONSIDERATIONS

The FDM method is a complex process that exhibits difficulty in determining optimal parameters due to the presence of a large number of mixed parameters that affect the quality of FDM products and material properties. The combination of parameters is determined by the type of filament and the size of the filament used in the FDM process [1]. Optimization of these parameters is essential for the improvement in various performance measures. The parameters can be classified into two general categories, machine and material parameters. The machine parameters are the parameters that the user specifies in the slicing software of the system and the material parameters are the properties of the filament material [5]. There are several parameters that should be considered: build orientation, layer thickness, raster angle, part raster width (infill density), raster to raster gap (air gap), necking, speed of deposition, cups height, melt flow rate through the nozzle and temperature. All of these parameters are influencing the dimensional accuracy, mechanical properties, surface roughness, manufacturing time and cost of the FDM product. The materials' thermal and mechanical properties influence the extrusion and performance of the print [5]. Process parameters of FDM are optimized based on the response requirement (dimensional accuracy, loading capacity, surface roughness and mechanical properties) [10].

The orientation parameter refers to the inclination of the part in the build platform with respect to *x*, *y*, and *z*. The axis *x* and *y* are lying parallel to the platform and axis *z* is the direction part build progression. The layer of deposited material depends on the type and speed of the nozzle, the minimum thickness of the layer may vary depending on the accuracy and application. The build orientation indicates the angle at which the longest length is inclined to the base. The inclination angle can be inclined at 0°, 45°, 90°, etc., this depends on the inputs of the user [5]. The orientation of part also affects other factors such as the build time, the complexity of support structure, shrinkage, curling, trapped volume, and material flow in FDM processes [3].

Other parameters for the FDM process are defined as follows: raster angle is the direction of the raster relative to the *x*-axis of the table, part raster width is the width of raster pattern used to fill interior regions of part curves, raster to raster gap is the gap between the raster of the same layer, necking is the shape formed due to the bonding between two rasters, cusp height is the nominal distance between facets and deposited part and speed deposition is the rate at which the nozzle deposits the raster [1],[3],[5].

The nozzle temperature necessary for melting and extrusion of the filament material and the temperature on the building platform is used for enhancing the adhesion of the layers. Both temperatures are important for successful FDM part modeling. Extension and platform temperature usually affect the dimensional accuracy of the part and the nozzle. The properly selected intensity of temperature will avoid blockage of the nozzle and damage to the machine. The selection should be done according to the recommendations and properties of the chosen filament material. Different filament materials have different thermal and chemical properties, that can influence the flow of the material and the glass transition temperature which is important for the overall quality of the part. The adhesion between layers is related to the local temperature and relative temperature between side-by-side filaments during deposition [45]. The bonding is done by molecular diffusion that is enhanced by the thermal energy of the extruded fiber in the molten state [46]. The side-to-side beads do not necessarily overlap and there may be a significant air gap.

The mechanical properties of the FDM part, such as strength and stiffness strongly depend on the strength of the fusion, bonding and the air gaps between the infill. The produced parts suffer from high anisotropy that also affects mechanical properties. Therefore, it is important to consider the anisotropy in the design process to optimize the functionality of the FDM-produced parts [48][49]. One of the solutions for this effect is reducing the number of layers in the design, by orienting the part flat on its larger surface area [48]. With increasing the layer thickness, parts show higher tensile strength and young's modulus. FDM parts are usually stronger along the layer direction and weaker along the building direction [47].

The processing parameters like slicing (layer) thickness, positioning and nozzle diameter are important for part accuracy, especially for assemblies, since they affect the shrinking, bonding and warping of the part [48]. Many researchers investigated the effect of parameters like raster width, part orientation, raster angle, layer thickness and air gap and their interaction on dimensional accuracy [56]. Studies are concentrated mainly on shrinkage along with the length and width direction of parts. Positive deviation from the required values is observed in the thickness direction. In order to minimize the change in part dimensions, optimum parameter settings using the Taguchi design method are suggested [50-52],[57].

Surface roughness is considered one of the important functional characteristics and a major challenging quest for researchers today. Parameters like extrusion temperature, width, layer thickness and build orientation directly affect the surface roughness of fabricated parts. As the thickness of the layer increases, the roughness increases. Also, the layer-by-layer building process causes the staircase effect on the surface and adversely affects the dimensional accuracy as well as the surface finish for different part build orientations. This can be reduced by decreasing the layer thickness and orienting the part such that the effect of the overall staircase is reduced [3],[10]. If the printed part requires a delicate surface finish, the attainable orientation will include multiple objective functions that must be adjusted to achieve the best result. This may include a change in filament type, which means that using post-processable materials may be a better option [55]. There are several publications that are describing approaches for enhancing quality in FDM processes [5],[53-54],[58]. According to them, wall thickness and layer height are the most significant factors for surface roughness as compared to the other factors. The optimal choice of the wall thickness and enhancement of the geometry of the eliminates the microstructural defects in FDM PLA products [5].

Fusing time depends on the speed of the axis that is driving the extruder, layer thickness and building orientation

[48]. If the part is oriented with the largest surface area as parallel to the layer plane, the fabricating time can be reduced. Also, one should take into consideration that there are other factors that influence the fabrication of FDM parts, if the layer thickness is smaller the longer the process will be or if there are no supports for the product the fusing time will be smaller. There are some basic guidelines to minimize production time: build an object with the largest surface on the bottom, maximize layer thickness, build holes facing upward, minimize the number of overhangs and minimize the height by making the largest dimension parallel to the building bed [46]. The process planning decisions are minimal by the designer to build the FDM component but is advisable to understand and study the options available in the original software, the build and support material characteristics. The planning should include shape evaluation of the part, the functional requirements, strength, surface quality and etc.

Several authors examined the impact of process parameters [48] but there is a lack of comprehensive analysis of the design guidelines for parts fabricated by FDM in terms of the process parameter. Determining the critical elements of the design is important to the overall effectiveness of the machine. Critical elements such as working environment, measuring surfaces, tolerances, hard-mounting points, datums, static and dynamic loading, handling, tool life expectancy and even storage will affect the way that FDM machines are designed. With FDM process products with complex free-form geometry, products can be fabricated and designers have the liberty of designing different functional geometries and interface features.

IV. CONCLUSIONS

In this paper, the basic concept of FDM process and filler materials production and types are summarized. Also, critical process parameters that affect the quality of processed parts have been discussed. There are many publications with extensive research focusing on experiments done on FDM products for different filament materials analysis and different process parameter optimization methods. The overall conclusions and results show that is necessary to optimize process parameters in order to improve surface finish, achieve better dimensional accuracy and mechanical properties for processed parts. With appropriate statistical designs and optimization techniques, complex parts can be produced at low cost compared to conventional manufacturing. The process does not need special tools and it's easy to control. With the FDM process there is no material wastage through cutting or machining and also can use biodegradable material that makes it even more eco-friendly. On the other hand, there are some drawbacks, it is a process that is more suitable for smaller parts, the raw materials are limited and it's a process that is still developing. In this paper, after the extensive review of the research on FDM it can be concluded that every aspect of factor and input parameters affect the quality and mechanical properties. Filament material composition, working parameters like speed and temperature, specifications of the FDM machine, and type of polymers are just a few of the many considerations that should be considered when optimizing the process.

FDM technology has unquestionably been successful in direct manufacturing due to high FDM part quality, which is determined by process settings, parameters, filler material, and design. Improper choice of these factors may lead to adhesion problems between the layers, high surface roughness and defects. The overall goal of the FDM technology is to produce high-quality products with high accuracy and expand its application in many industries. This study proposes future research on the design of FDM parts in order to use the full potential of the process and indicates that some relationships between the factors and parameters influencing the process are still unclear and need further investigation.

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