EFFECTS OF PROCESS PARAMETERS ON THE MECHANICAL PROPERTIES OF FUSED DEPOSITION MODELLING OF POLYMERIC COMPOSITES: A REVIEW

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ABSTRACT

Fused deposition modelling (FDM) technology has grown from fabricating conceptual models and prototypes to fully functional polymeric parts. However, FDM produced parts suffer from poor mechanical and physical properties. To improve the quality of FDM printed parts, control of process parameters is required. This paper presents a review on the effects of process parameters, namely print speed, extrusion temperature, layer thickness, air gap, part build orientation, as well as, hatch width and spacing, on the physical and mechanical properties of FDM produced polymer composites. The paper further discusses various methods used to rationalise the process of optimising these process parameters.

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1. INTRODUCTION

Additive manufacturing (AM) has brought ease within the manufacturing industry by making it possible to produce geometrically complex, strong, light weight products, at lower cost with no additional tooling required [1]. Contrary to subtractive manufacturing methods used in conventional manufacturing, AM consists of the addition of material in a layer by layer format to form fully functional three-dimensional (3D) objects [2]. This technology has found wide application in the aerospace, automobile and medical implant industries [1]. The quality of AM parts relies also on the selection of feed stock material, which significantly impacts the mechanical properties and performance of produced parts. Polymers, metals and ceramics are materials that are commonly used as feed stock for AM processes [3]. Selective laser sintering (SLS), Stereolithography (SLA) and fused deposition modelling (FDM) are AM technologies that produce parts with superior mechanical properties in comparison with other methods such as binder jetting (BJ) and laminated object manufacturing (LOM) [4,5,6]. Unlike SLS and SLA process, FDM machines are office friendly and are available in a desktop size at low prices, which makes the technology more accessible and cost effective [7]. Despite the advantages that AM has brought within the manufacturing industry, much still needs to be done to fabricate parts with equal mechanical properties, dimensional accuracy and surface finish as compared to their counterparts produced through traditional manufacturing methods such as injection moulding for plastics, casting and machining [8,9]. Accessibility, user friendliness and broad range of materials that can be processed makes FDM the most widely used technology amongst other available AM methods [9]. Fused deposition modelling thermoplastic filament material is extruded through a nozzle onto a build platform, layer by layer until a three-dimensional object is formed (Figure 1) [3,10].

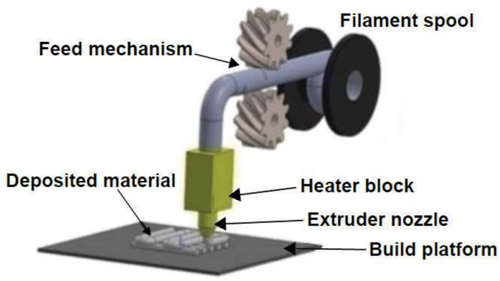

Figure 1: Schematic of the FDM Manufacturing Technique [10]

The dimensional accuracy, surface finish mechanical and physical properties of the end-use products constitute important criteria of the performance of printed parts [8].Thus, understanding the impact of process parameters on the mechanical properties of FDM prints could help with the best selection of the optimum combination of process parameters to improve the properties of the parts [11,12]. This paper presents a review on the effects of FDM process parameters, namely print speed, extrusion temperature, layer thickness, air gap, part build orientation, as well as hatch width and spacing, on the physical and mechanical properties of FDM produced parts using polymer composites as feedstock materials. Furthermore, the review also elaborates on the ways FDM process can be improved for better quality of manufactured parts in order to expand its application in various industries.

2. FUSED DEPOSITION MODELLING AND FEEDSTOCK MATERIALS

Fused deposition modelling allows a variety of thermoplastic materials to be used, that can be mixed with fillers to improve their mechanical and physical properties [8]. However, FDM still faces drawbacks such as poor mechanical properties, anisotropy, high levels of porosity, poor surface finish and dimensional inaccuracy and this limits its expansion in manufacturing industry, thus hindering the commercialisation of parts fabricated through FDM [1]. [7]. Thus, identification of process parameters that affect the quality of parts and the FDM process as a whole is very important. The FDM process is an interconnected manufacturing process in that the material that is selected to perform the building process also plays a significant role on the outcome of the object to be produced. Proper optimization of process parameters and the selection of appropriate feedstock materials in FDM constitute critical factors determining the attainment of high performing end use products [10].

In addition to the advantage of a wide range of thermoplastic materials to choose from, the materials are quite easy to print with and are also environmentally friendly in terms of recyclability [7]. Ideally, materials with no warpage, shrinkage and moisture absorption, with high strength and durability are preferred for the FDM process [13]. Thermoplastic materials range from amorphous, semi-crystalline to elastomers. Amorphous materials possess low solidification shrinkage, which is one of the aspects that make it possible for them to be processed through FDM. Their melt viscosity is low due to small differences between the processing temperature and the polymer glass transition temperature [14]. Semi-crystalline polymers perform well in applications involving wear, structural loads, and chemical resistance. Exceptional properties including high durability, easy to process materials, biodegradability and thermal stability make elastomers valuable for tissue engineering applications. The most commonly used polymer materials in FDM include acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonates (PC) and nylon, which produce prints with good characteristics and performance [15,16]. The properties of melting temperature, glass transition temperature and coefficient of thermal expansion for these materials determine how mechanically sound printed parts will be [14]. However, much still needs to be done to minimize drawbacks of FDM such as poor mechanical properties which further limits expansion in the applications of the technology. Clearly, it is necessary to understand the relationship between material properties and process parameters in order to improve the quality of FDM parts [2].

3. SURFACE FINISH OF FDM POLYMERIC COMPOSITES

The properties and quality of additively manufactured parts rely on the build process. Utilisation of the FDM manufacturing technique is affected by poor mechanical properties and aesthetic conditions of the components it produces which further limits its application in various manufacturing fields [11,17]. Surface quality, which is measured as surface roughness, is used as a measure of quality and is still a major setback of the FDM technique [16,18]. The existence of or increase in surface roughness is due to the staircase effect in building; an inherent disadvantage in the layer deposition manufacturing process [18]. Although it can be time consuming and costly to manufacture using thinner layers, larger layer thicknesses increases the surface roughness [18]. The staircase effect is aggravated by complex part geometry and results from a mismatch between the volume of extruded material and the volume of material set by the computer aided design model [19]. Overlapping of successive layers occurring during building gives rise to parts with rougher surface finish. Curves or inclined surfaces increase the surface roughness, except when they occur in the horizontal plane. Parts with better surfaces are normally obtained by orientating the largest flat surface of the print parallel to the print bed and through upright printing direction with reduced layer thickness from 0.4 mm to 0.1 mm [20]. Optimising process parameters greatly improves surface finish and further decreases time and cost for post processing using techniques such as chemical treatment, laser treatment, heat treatment or ultrasonic treatment [21]. Figure 2 shows poor the surface finish of an FDM printed part in the form of deposited filament lines.

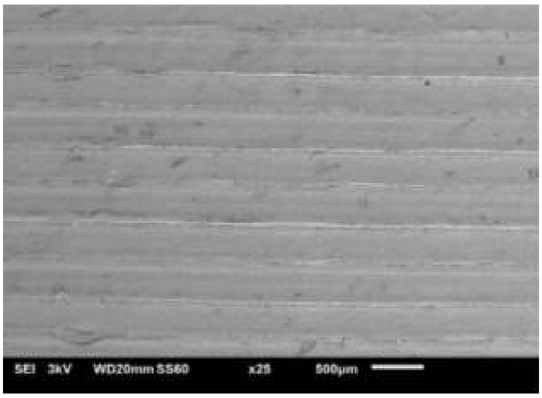

Figure 2: Poor Surface Finish of an FDM Printed Part [22]

3.1 Methods of Post Process Surface Finishing

Acetone and dichloromethane are chemicals that can be used on fully functional part to reduce their surface roughness, and further improve their mechanical properties [20,22]. Printed components are treated with a CO_2 laser to minimize their surface roughness in a process where the material is heated and softened to eliminate unnecessary irregularities on the surface [22,23]. Heat treatment or annealing is the most widely used post-processing method to enhance the surface quality and mechanical performance of the FDM prints. When heat is applied to a part, the layer-to-layer gaps are filled, causing a finer surface quality [23]. At the glass transition temperature, the molecular surface tension of a material is minimized, causing the material to flow on the surface due to the attendant reduction in viscosity [23]. Therefore, the material flows to fill existing pores and gaps on the surface, as well as gaps in the staircase effect in between layers, resulting in smoother surface finish and better mechanical properties [17]. Ultrasound can be employed to reduce stair case effect during and after printing to improve the surface quality of the print [24]. The technique is applied to improve the impregnation of polymer into fibre bundles and therefore, enhance bonding between them [21]. Ultrasonic transducers can be attached to the print platform to provide vibrations, which lead to a reduction of the staircase effect and an improvement of the surface finish [22,23]. Ultrasounds are applied to finished parts, leading to fusion of voids and gaps in them. The method offers the advantage of not causing any chemical reaction during the process [24]. Figure 3 shows an FDM print after being exposed to surface treatment. It is found that available post processing methods are able to improve the surface finish of FDM parts.

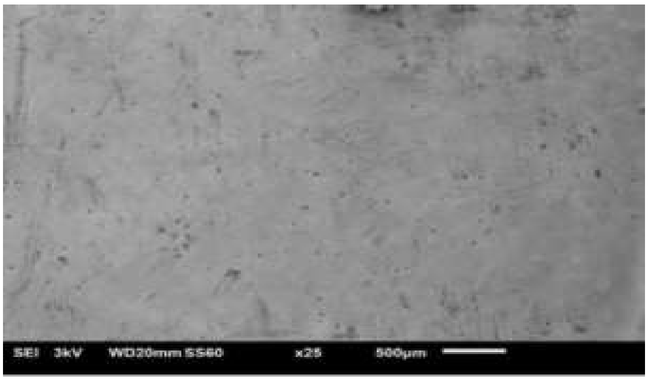

Figure 3: Post Surface Treatment of an FDM Printed Part [22]

4. DIMENSIONAL ACCURACY OF FDM POLYMERIC COMPOSITES

Although the FDM manufacturing process is regarded as the most widely used method in comparison with other AM technologies, FDM produced parts suffer from poor dimensional accuracy. Fused deposition modelling involves heating thermoplastic filaments just below their melting temperatures, then extruding them and finally allowing them to cool in air until they solidify [8,9]. Uneven heat transfer between the previously deposited layer and the newly formed layer of a print creates internal stresses. Moreover, this temperature difference results in dimensional inaccuracy as the part contracts due to cooling [12]. Thermoplastic materials with a high degree of crystallinity and fast rate of crystallisation tend to shrink, warp and distort, which leads to the production of dimensionally inaccurate parts [25]. Due to rapid heating and cooling cycles of successive extruded layers, residual stresses arise between them that affect the shape and dimensions of the final parts [26]. Inclusion of fibres in matrices enhances the properties of the built part but comes with some negative effects such as increased void content in the printed parts. This, together with uneven fibre distribution within the fibre-reinforced thermoplastic filament and poor bonding between fibres and matrix, further contributes to the distortion of printed parts [27]. Maximizing the dimensional accuracy of FDM built parts requires consideration of certain factors such as the orientation of the largest part side should be parallel to the build platform and the part be built in the z-axis direction [28,29]. Addition of supports if needed and the addition of a thin layer around the part to assist and increase the contact surface between the part and the powder bed to improve the dimensional accuracy of printed parts are other considerations [30,31]. Addition of a thin layer of glue or tape on the bed increases adhesion of the base of the print with the platform and act as a release agent when printing is finished [32,33].

Fused deposition modelling is a process parameter dependent manufacturing process. Therefore, selection and controlling the process parameters is necessary for optimum results. Material deposition rate and flow rate influence each other to maintain a constant raster width during the manufacturing process [31]. An excess of material extrusion gives rise to wider layers that lead to overlap and if not enough material is extruded gaps develop between tracks [12]. A wider raster width tends to improve bonding between adjacent tracks and improves the mechanical properties but leads to a reduction in the dimensional accuracy of built parts [32]. A smaller raster width on the other hand will ensure good dimensional accuracy but leads to an increase in manufacturing time and costs.

Improvement of productivity through simple and faster manufacturing techniques, without compromising quality, safety and reliability of manufactured parts, is a growing demand [33,34]. Taking thorough control of all parameters associated with the manufacturing process will improve the properties and performance of manufactured parts [33]. Surface quality, dimensional accuracy, physical condition and mechanical behaviour of FDM printed parts depends on the control of process parameters including layer thickness, extrusion temperature, print speed, air gap, part orientation, as well as hatch width and spacing [35]. Thus, selection of an optimum set of process parameters is an important procedure that guarantees enhanced properties of FDM prints [36]. The selection of improper process parameters set leads to poor mechanical properties of printed parts, and escalation of build cost, time and material. The effectiveness of FDM process parameters depends on the material being used, as ideal parameters obtained for one material will differ from those of another material [37]. Materials such as nylon exhibit better functional properties such as low shrinkage, chemical wear and thermal resistance than other materials that are normally used such as ABS and PLA [38]. Due to these benefits, nylon is widely used in manufacturing home appliances, as well as aerospace and automotive engineering applications. The strength of FDM fabricated parts is usually less when compared to that of parts obtained from conventional manufacturing processes such as injection moulding.

5. PROCESS PARAMETERS THAT INFLUENCE THE QUALITY OF FDM POLYMERIC PARTS

A detail of some of process parameters mentioned here that influence the physical and mechanical properties of FDM prints is now presented.

The process capability of any manufacturing process is determined by the ability of the process parameters to produce parts with good mechanical performance [32]. Layer thickness affects both the surface roughness and dimensional accuracy of FDM prints [11]. Investigations of ABS and PLA have shown that surface roughness can be minimized by the use of lower values of layer thickness during printing [39]. Lower layer thicknesses give rise to parts with higher values of tensile and flexural strength [40]. Research has confirmed that increasing the layer height of the prints generates more voids in the microstructure, with the attendant reduction of the tensile strength of print parts [41]. Enhancement of the tensile strength of printed parts for lower layer thicknesses is the result of creation of stronger interlayer bonds [37]. The layer thickness in FDM typically lies within the range of 0.05 mm – 0.5 mm [42]. A study of PLA builds with layer thicknesses of 0.125 mm, 0,250 mm and 0.500 mm, showed the build with lowest layer thickness to have the highest value of elastic modulus and lowest surface roughness, despite taking more time to print [43]. Build time and layer height governs the productivity rate as, the more time it takes to print the lower the productivity. However, increasing layer height reduces the aesthetics of prints due to the presence of voids. Other studies carried out on ABS with layer thicknesses ranging from of 0.075 mm to 0.5 mm produced parts with higher values of ultimate tensile strength and higher hardness for the lower layer thicknesses [43]. Comparison of the effects of layer thickness for PEEK and ABS that was done for layer thickness of 0.2 mm, 0.3 mm and 0.4 mm showed improved properties at lower layer thickness of 0.2 mm and 0.3 mm. The average tensile strength of PEEK was found to be 108% higher than that of ABS [44]. Figure 4 shows the various process parameters discussed in this section.

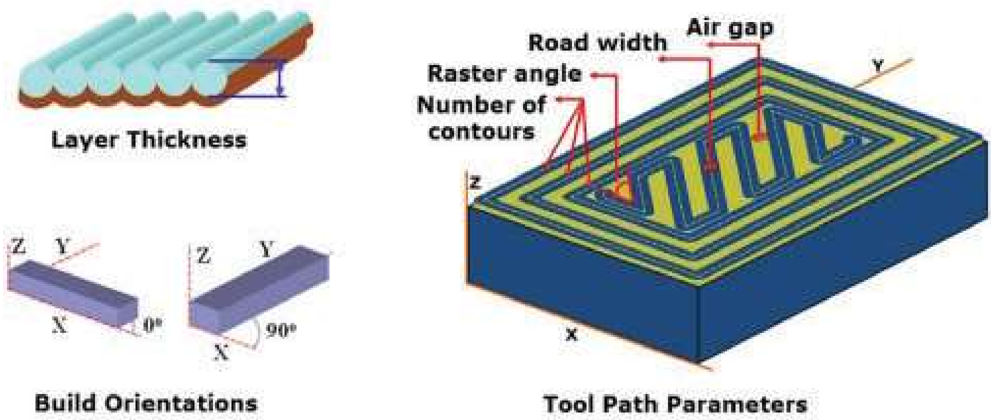

Figure 4: Fused Deposition Modelling Process Parameters [44]

Parts that are printed through the FDM process exhibit anisotropic properties as a function of the different build directions adopted, which affects their overall strength and appearance [44,45]. Build orientation significantly affects the mechanical properties of printed parts, particularly tensile and compressive strength [46]. It also influences the surface quality, geometrical accuracy, manufacturing cost and overall build time of parts [47]. Prints built in a direction parallel to the tension forces results in the higher tensile strength and stiffness than those built in a direction that is perpendicular the pulling forces [48,49]. Studies indicate that the strongest tensile performances of printed parts are obtained when the printing orientation of the filament extrusion is parallel to the direction of the applied force [49]. Part geometry can also make it impossible to achieve the best desired quality of FDM parts. Parts with concentric features resolve best when layers are printed parallel to the xy-axis [50]. Designing a part so that fragile and concentric features grow in the same direction will help determine the best orientation for a part to print [49].

The two thermoplastic polymers, PLA and ABS, that are commonly used in FDM, manifest maximum tensile strength at build orientation angles of 0° followed by 45º and then 90º to the direction of extrusion of filaments [17]. Specimens built on flat (XY) orientations have higher ultimate strength in comparison with upright ones (Z-direction) and on-edge building (XY) orientation [9,50].

The air gap sizes between layers predicates the strength of prints. Lower levels of voids improve the tensile strength of FDM printed materials [12]. Negative air gaps which arise due to overlapping of successive adjacent layers forms denser structures, thus making parts much stronger [18]. Presence of voids prevents effective transfer of stresses and results in parts that loose integrity at a lower stress levels [51]. The formation of void regions can be minimized by employing smaller layer thicknesses as it enhances the bond strength between layers, which reduces the interlayer distortion that causes micro voids if no pressure is applied during FDM [30].

Good quality FDM parts are obtained using thermoplastic polymer materials with low melting and solidifying temperatures, low viscosity, and minimal shrinkage to avoid prints with poor quality [14]. A low printing speed with low layer thickness gives better bonding with the previous layer to produce parts with better tensile and flexural strength. Poor interlaminar bonding between layers will result from increasing printing speed [51]. The most commonly used printing speed for polymeric materials that are normally processed through FDM ranges from 15 to 100 mm/s [51].

Printing temperature influences the rheological behaviour, crystallinity, deformation, and interlayer bonding strength of polymeric filament layers, which further influences printability and the physical and mechanical properties of FDM printed components [12]. Most polymeric materials can be processed at extrusion temperature of 200 to 270^{0}C [52,53]. Even though use of higher temperatures is generally known to result in parts with stronger interlayer bonding, parts with excellent tensile strength were obtained at a moderate temperature of 190^{0}C with PLA [54].

Hatch space is the separation between two adjacent hatch lines and is significant to ensure a high-density and minimum porosity on printed parts [55]. Changing of hatch distance leads to modification in the geometric characteristics of tracks and, consequently, surface morphology [56]. With larger space between hatch lines, undesired surface effects such as rough and porous surfaces are likely to arise [57]. Good quality parts require settings that lead to the formation of an overlap between adjacent hatches [58]. Reducing the hatch spacing parameter and introducing overlap assists in minimizing the emergence of air voids within the layers. However, when the hatch spacing is above 0,17 mm, the relative density of printed parts reduces drastically, which affects both the physical and mechanical properties of produced parts negatively [59].

5.1 Optimisation of Process Parameters

Conventional manufacturing process such as injection moulding fabricate parts with better mechanical properties and good surface quality in comparison to FDM produced parts [60]. To improve these qualities in FDM, it is mandatory to understand the interconnection between material properties and process parameters before application of optimisation techniques. Optimisation of FDM process parameters can be achieved through various methods such as group method for data handling (GMDH), differential evolution (DE), quantum–based particle swarm optimisation (QPSO), Taguchi, response surface methodology (RSM), genetic algorithms (GAs), Process capability ratio technique for order performance by similarity to ideal solutions (PCR-TOPSIS), particle swarm optimisation (PSO), Bacteria foraging optimisation (BFO), desirability function, fuzzy logic, particle swarm optimisation–bacteria foraging optimisation (PSO–BFO), and non-dominated sorting genetic algorithm (NSGA) to mention a few [5]. Successful industrial application of the aforementioned methods indicates the Taguchi and RSM methods to be the most effective, reliable, and simple to apply in identifying critical process parameters. The ANOVA method cannot be utilised to regulate optimum process conditions in cases of multi quality optimisation [6]. This is because the method cannot supply accurate results if sample cases are dependent on each other. With ANOVA, all population means and all variables from each data group must be roughly equal and this is rarely possible in real world applications [5,6]. For a large number of process parameters, the RSM method can be time consuming in comparison with the Taguchi method. With the Taguchi method, identification of critical FDM process parameters and their improvement can be achieved at lower costs and is thus preferable [1].

6. CONCLUSION

The foregoing study shows that the quality of FDM printed parts is dependent on both the proper selection of materials as well as careful setting of process parameters. The study highlights the most critical process parameters as; layer thickness, extrusion temperature, air gap, printing speed, hatch width, hatch spacing and printing path direction. Surface roughness and dimensional accuracy of printed parts are affected more by the layer thickness than hatch width and printing speed. Air gaps between layers, contributes to failure of printed parts by delamination and be reduced by minimizing the layer thickness. Reduced hatch spacing leads to enhanced physical and mechanical properties. High printing temperatures and low printing speed both lead to the creation of stronger interlayer bonds and therefore production of parts with better mechanical properties. The printing direction is shown in the study to be significant with the best properties obtained for parts that are built in the x or y directions.

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