Effect of process parameters on additively manufactured parts using FDM process & material selection: A review

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Abstract. Fused deposition modelling (FDM) is second most widely used additive manufacturing process worldwide. Performance of the FDM system is highly effected by number of parameters such as environmental factors, material properties, part orientation and supports, machining parameters and working parameters. Working parameters specifically raster angle and width, layer thickness and amount of infill highly effect the mechanical characteristics of additively printed parts. Part orientation which is directly proportional with support generation, is mandatory requirement for hanging parts but it results in poor surface finish and require more post-processing. A proper selection of material is one to the key factor of success of functional prototypes produced from FDM system. Various materials categorized as biodegradable/non-biodegradable, biocompatible, water soluble/insoluble, etc. can be processed on considered system. A various commercial and open ware software’s can be used to identify optimum value of working parameters for best results. In present work, a comprehensive review has been carried out to check the effect of working parameters on the performance of the FDM printed parts. Study also supported by the understanding of the various materials reinforced by FDM system and new possibilities are identified for future work.

1. Introduction
In today’s well established competitive market, many companies fighting for self-stability by putting countless emphasis on product diversity and reorganization. Due to this many manufacturers led innovative products and concentrated on function markets. This results in defilenent of the basing product design cycle in which traditionally product goes through several steps i.e. idea to final product. The shorter product life cycle due to rapidly changing fashions and trends required replacement to traditional manufacturing approaches [1]. The solution for these problem resolute by the use of additive manufacturing (AM) process. The first commercial additive manufacturing system developed by 3D systems in 90s. In less than three decades the technology has been evaluated tremendously and number
of AM systems available in market which can process curable liquids to polymer and from polymer to metals [2].

Additive manufacturing broadly classified into three categories, liquid, powder and solid based system. The basic working principle of all systems is somewhat same i.e. based on layer by layer manufacturing, but the way of execution is different. Solid based systems based on chemical, thermal and mechanical properties of used material [3]. Extruders used in these systems are used to heat solid material to semi-liquid state and then deposit it on the surface by using some mechanism. Solidification of the deposited material results due to variation of temperature and pressure of extruder and working environment [4]. Extensively used solid based AM systems such as Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), Paper Lamination Technology (PLT), Multi-Jet Modeling System (MJM), Model Maker and Pattern Master, Slicing Solid Manufacturing (SSM), Melted Extrusion Modeling (MEM) are commercially accessible in market [2], [3], [5], [6].

AM systems vary as per their applications, on the basis of the process, the sources of energy, size of prototype, etc. In this work, a basic overview of solid based systems known as fused deposition modeling with detailed explanations of working principle, process parameters which effect characteristics of printed parts and the material used. Consequent section enlighten the working principle of FDM system.

2. **Fused deposition modeling (FDM)**

Fused deposition modeling (FDM) is second most widely used additive manufacturing technology, after stereolithography appratus. A solid plastic material in the form of a filament is unwound from a ring and delivered to an extrusion nozzle. The nozzle is heated to controlled melting temperature of the plastic and the flow of melted plastic is controlled by on/off mechanism.

2.1 **Working principle of FDM**

The principle of the FDM is based on layer by layer manufacturing, thermal energy and chemical composition of the raw material. The material in the form of filament wounded on spool is melted in a especially intended head known as extruder, which deposit material on the model. As it is extruded, it is cooled rapidly due to variation of temperature and pressure and thus solidifies to form the model. The model is built in layers, like the general AM systems. Factors effecting performance of system and strength of the printed parts are environmental factors, working parameters, machine parameters, and material characteristics [1].

In fused deposition modelling system, filament of plastic feeds to extruder or nozzle through a feeding mechanism. Filament diameter or rod diameter is one of the important factor while operating the system. Extruder’s heat the filament to semi liquid state and extrudes it in a thickness typically of 0.25 mm. Outlet thickness of deposited filament has direct influence on strength and aesthetics of printed part [2].

A refined automation system comprises of servo controls, sensors and precise NC system grip the extruder to deposit filament according to path generated by software [3]. In Figure 1 is shown the basics fused deposition modeling process. Platform of FDM system can be fixed on movable in x-y direction depending on the setup designed by manufacturer. The main advantage of this system is that is does not require any chemical post processing like liquid based system and other post processing are comparatively easier to do [4]. The disadvantages are poor control of z-axis, surface finish due to generation of support. FDM system able to print complicated parts but it may take days to print. This can be reduce by increasing deposition speed but it has limitation due to high viscous nature of molten plastic. Lead time can be reduced by changing the percentage of fill from fully dense to sparse mode [5]. FDM system can be operate with wide range of materials categorized as water soluble/insoluble, bio degradable/non degradable, bio-compatible/non compatible.
Figure 1. Working of Fused deposition modeling [6]

FDM software require a CAD model in IGES or STL format as input. STL (standard tessellation language) file is de-facto standard of all additive manufacturing systems developed by 3D systems in 1983. STL file can be in binary or ASCII format. Both the formats provides the model in tessellated from i.e. triangular facets [7], [13]. Consecutive section high lighten the various process parameters that influence on the working of FDM process.

2.2 Parameters in Fused deposition modeling

A short working of fused deposition modeling has been explained in previous section. In various types of additive manufacturing processes, FDM finds a great scope in manufacturing and research due to wide range of raw materials, low cost set up, ease in handling of machine and many more. In order to satisfy customer needs and satisfaction, proper selection of process parameters of FDM machine is necessary. Consequent section review the importance of various process parameters used in FDM process.

2.2.1 Orientation and Support

To obtain a good result from FDM 3D printing, it is necessary to determine the optimum process parameters. Proper process parameters insures the quality of printed object, precision in dimension, reduce the wastage of material and reduces the production time and cost [14]. FDM machine is easy to handle but difficult to understand. This is due to large number of process parameters which makes it complex. Strength of 3D printed parts can be enhanced by selecting proper machine and working parameters [15]. Figure 2 shows all the factors and variables that need to be studied to optimize the performance of FDM process.

FDM parameters can be categorized as working parameters, unprocessed parameters, environmental parameters, machine parameters, part orientation, etc. Part orientation is refer to the way the part built on the platform w.r.t. x, y, and z axis. Part orientation followed by support style is another important factor need to consider while printing the object [16]. Support style is the printing style of object to prevent the part from collapsing during building process [17].

2.2.2 Working parameters

Working parameters of the FDM includes air gap, raster angle, raster width, part interior style, layer thickness, infill pattern, number of loops/contour width, etc. Layer thickness is refer to the thickness of the filament [18] placed by nozzle tip as shown in Figure 3(a). Raster width is the width of the material bead used for the raster. More the value of raster width exhibit more strength in printed part, whereas less value results in less production time and less material consumption. The value of raster width varies with the size of nozzle [19], [20].
Figure 2. Process parameters in generalized FDM process.
Air gap refers to the gap between adjacent raster tool paths as shown in Figure 3(b). One of the important working parameter is raster angle. It is the angle of raster pattern with respect to x-axis on the bottom part layer. It is very important parameter as it directly effect on the strength of the printed part. Its value varies from 0° to 90°. Number of loops refers to the deposition of the number of filaments adjacent to skin. Infill parameters refer to the filling percentage of material in each layer of the print. For 100% fill, print pattern is always straight, however in case of fill of less than 100% pattern can be strength, circular or polygonal. Infill pattern are shown in Figure 3(c) [12]. Figure 4 shows various approaches of orientation for print [21]. Part orientation followed by support style is another important factor need to consider while printing the object.

![Figure 3. Various parameters used in FDM (a-c)](image)

2.2.3 Unprocessed parameters

Unprocessed parameters generally refer to density and the color of the material. As these two generally not effect on quality of printed part. Environmental factors need to be consider while selecting the proper material for printing. This includes temperature and humidity. As most of the materials used in FDM are of plastic category, these materials are highly effected by humidity and environmental temperature. To avoid the effect of these factor, a close working environment is required [23].
2.2.4 Machine parameters
FDM machine parameters include nozzle diameter, envelope temperature and machine calibration. Standard nozzles used in FDM machines are of diameter range 0.4 to 0.5 mm. Though 0.3 mm also available for special materials [24].

3. Literature survey
There has been wide-ranging research carried out by various researchers on the process parameters optimization of FDM process. Most of the researchers directed the research on optimizing surface roughness/finish, improvisation in mechanical properties. In the following sections, a comprehensive literature survey presented on the basis of process parameters and material used in FDM process.

3.1 Process parameter optimization
There has been wide-ranging research carried out by various researchers on the process parameter. In fused deposition modeling type of additive manufacturing process, various parameters effect on overall efficiency of printed part. Out of several parameters, process parameters has highest effect on quality of the printed part. Process or working parameters includes raster angle, raster width, air gap, nozzle diameter, temperature and many more [25]–[32]. Some of these are primary factors which have major impact on printing and the primary reason that most of the researchers concentrated on these parameters. To evaluate the effect of various parameters, it is necessary to check the effect individually while keeping other as constant. Kaveh et al. [19] considered extruded temperature, feed rate, flow rate and raster width as process parameters to enhance the dimensional accuracy and intrinsic internal cavities of the printed object. Raster angle has direct influence on the strength of the printed object. Finest raster width for each layer thickness lead to reduce air gap between rasters. Temperature is process as well as machine parameter which is important to consider for precision and internal cavity. For the considered material, 210°C was selected as the optimum temperature.

Raster angle which decide the orientation of the filament in the printed part, responsible for the tensile strength. Orientation of the filament can be set between 0° to 90° and strength varies with the variation of the angle. So, it is necessary to decide optimum value of the raster angle for maximization of the tensile strength. Ning et al. [33] examined the outcome of the raster angle and infill on the tensile strength of Carbon fiber-reinforced plastic (CFRP) composites printed using FDM. In case of CFRP material, raster angle of 0° and 90° exhibit larger Young’s modulus and yield strength than 45° whereas increase in infill speed results in reduction in strength due to poor bonding between adjusted rasters and consecutive layers.

Wenzheng et al. [34] inspected the impact of layer thickness and raster angle on the general mechanical characteristics of 3D printed polyether-ether-ketone (PEEK) objects. The average tensile strength of PEEK parts where considerably high compared to acrylonitrile butadiene styrene (ABS) parts. Compressive strength and bending strength shown considerable improvement as compared to later. Vaezi et al. [26] investigated the effect of the layer thickness and binder saturation level on the 3D printed parts and also predicted the mechanical characteristics based on average stiffness method. Results of experiment conclude the increase binder level increase tensile strength while increase in layer thickness decrease tensile strengths and increases flexural strength.

Tool path is important factor to ensure proper outcome from the system. Tool path generation approach consist of three important sections that are identification of inclination, generation of the tool path in each sub-section and connection between discrete sub-paths. Jin et al. [35] applied optimization in tool path generation in deposition modelling. The approach is useful to generate the direction parallel to tool path based on dissimilar priorities. Sood et al. [36] used weighted principal component analysis to optimized five process parameters of FDM at three different levels.

Number of process parameters in FDM system are more which leads complication while handling multiple parameters. It is necessary to build relation between various process parameters. Lee et al. [37] optimized four working parameters that are air gap, raster angle, raster width and layer thickness, with humidity and temperature as constant with three levels. Used Taguchi’s method to build relation
Table 1. Summary of the FDM process optimization

| Author           | Material used     | Process Parameters                                                                 | Remark                                                                 |
|------------------|-------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Kaveh et. al. [9]| HIPS              | Extruder temperature, Feed rate, flow rate and raster width                        | Improved dimensional accuracy and reduction in intrinsic internal cavities |
| Vaezi et. al. [10]| ZP102 powder and Zb56 binder | Layer thickness and binder saturation level                                        | Evaluated two layers of thickness 0.1 and 0.087 respectively, at the 90% and 125% binder saturation levels. Higher the binder level, higher the tensile and flexural strengths but results in poor dimensional accuracy and surface uniformity. |
| Farzad et. al. [11]| Calcium sulfate powder | Layer thickness and print orientation                                              | Evaluation of considered parameters results in higher toughness, compressive and tensile property with 0.1125 and 0.125 mm layer thickness. Analytical model represented the variation in strength and stiffness properties for considered material. Experimental results show significant similarity with 4% error. |
| Croccolo et. al. [12]| ABS M30          | Part build direction, raster angle, bead width, air gap, layer thickness and number of counters | Analytical model represented the variation in strength and stiffness properties for considered material. Experimental results show significant similarity with 4% error. |
| Hill and Haghi [13]| Polycarbonate    | Raster orientation                                                                  | Print orientation has high influence on the mechanical characteristics of the material. Failure mechanism correlated with fibre-reinforced composites model. |
| Ulu et. al. [14]  | Material not specified | Build Orientation                                                                  | Developed orthotropic material-model. Nine parameters essential to be resolve experimentally. The Young’s moduli, shear moduli, and Poisson’s ratios for the three principal directions where evaluated with the model. FEA simulation and experimentation shown close relevance to output of numerical model. |
| Espin et al. [15]  | Polycarbonate    | Build orientation, nozzle diameter, slice height, and diameter of the extruded filaments | Proper orientation results in improved yield strength. Tensile stresses should be perpendicular to layer’s planes to avoid fragile fracture. |
| Ning et. al. [16]  | CFRP              | Raster angle and infill speed                                                       | Raster angle of 0° and 90° exhibit larger Young’s modulus and yield strength than 45° |
| Wenzheng et. al. [17] | PEEK and ABS     | Layer thickness, Raster angle                                                      | The outcome concluded that the average tensile strength of PEEK parts where considerably high compared to acrylonitrile butadiene styrene (ABS) parts. |
| Jin et al. [18]    | ABS               | Tool path generation                                                               | Tool path generation approach consist of thee important sections that are identification of inclination, generation of the tool path each sub region and connection between individual sub-paths. |
Weighted principal component analysis to optimized five process parameters of FDM at three different levels. Improved dimensional accuracy

Throwing distance and elasticity were considered for the optimization in FDM process.

Nano composite deposition system (NCDS). Experimental investigation results in higher mechanical properties with optimal build direction. Also, results evaluated that 3D printer parts have low compressive strength as compared to other techniques.

Investigated the effect of stacking sequence of composite. The distinctive behaviour of angle-ply laminate, under impact loading due to its pseudo-ductile behaviour, flexural damage testing has been assessed.

New methodology based on multi materials as reinforcement. Uni-axial tensile test and fracture test shows that reinforcement results in superior mechanical characteristics.

Environmental parameters results in the decreased of the tensile strength by 67-71 per cent in hot, wet environments related to dry, room temperature conditions.

| Raster angle | ABS [25] | Polypropylene [26] | Polycarbonate [13] | PLA [26] |
|--------------|----------|--------------------|-------------------|---------|
| 90°          | 26       | 32                 | 19                | 54      |
| 0°           | 34       | 36                 | 59.7              | 58      |

| Material                  | References            | Remarks                                                                 |
|---------------------------|-----------------------|-------------------------------------------------------------------------|
| Polylactic Acid (PLA)     | [7,10,16,19,21,27,28] | Polylactide (PLA) is widely used and biodegradable thermoplastic polymer. The unique mechanical characteristics make it superior than the other thermoplastic polymers. Various process parameters like part orientation, raster angle, raster width and infill significantly help to enhance the properties of PLA parts. Comparison of mechanical characteristics of PLA with other thermoplastic polymers has been summarized in table 2. |
| **Acrylonitrile Butadiene Styrene (ABS)** | \[4,12,24,29–34\] | ABS has high toughness, a high degree of moldability, and low thermal conductivity. Number of variants of ABS are available with number of different characteristics like colors, strength, thermal conductivity, etc. ABS P500 is suitable for medical and pharmaceutical applications due to its high strength. ABS-M30 is one of good replacement to virgin ABS as it is 25-75% stronger, higher durability and ideal for realistic functional test. One of the reason for wide popularity of ABS is its compatibility of combination with various materials like organic modified montmorillonite (OMMT), UHMWPE, Jute fiber, Aluminum oxide, Zinc oxide. ABS also can be added with copper and iron nano particles to enhance thermal conductivity of the base ABS. |
| **High Impact Polystyrene (HIPS)** | \[9,24\] | HIPS is a thermoplastic material which dissolve in d-Limonene. Due to its lightweight nature is frequently preferred as support structure material with ABS models. As it dissolve in d-Limonene, it is easy to remove support structure and post processing decidedly reduce. Also, its properties close to ABS, make it dual extruder partner with latter. For the parts which may get worn out or for the lightweight applications, HIPS is dimensionally stable and quite well-lit than ABS. |
| **Polypropylene (PP)** | \[35,36\] | The most cost effective 3D printing material which repel to allot of chemicals and solvents. Sometime, ethylene co polymerising with PP to higher strength. At room temperature, PP repel to all organic solvents and fats. Whereas, sylene, tetralin and decalin i.e. non-polarity solvents used to dissolve PP. Due to rigid and robust nature of PP, it used in textile, ropes and stationary applications. |
| **Polyether–ether–ketone (PEEK)** | \[17,37\] | Similar to ABS P500, PEEK is medical grade material with very high temperature for printing. It frequently used in medical, pharmaceutical and food packaging applications. Also, good impact resistance, superior adhesion between layers makes is suitable for aerospace and oil industry. In 3D printed parts, PEEK shows superior mechanical properties than ABS. |
| **Carbon fiber filaments** | \[16,38,39\] | To increase the strength and stiffness, carbon fibre filaments reinforced into base material like PLA or ABS. number of filaments come together with carbon fibre like PLA, PETG, Nylon, ABS, and Polycarbonate. Carbon fibre reinforcement helps to enhance mechanical characteristics like tensile strength in un-axial or bi-axial direction. Whereas, it also leads clogging in extruders due to small fibres of carbon into filaments. |
between various working parameters. Throwing distance and elasticity were considered as performance criteria for the optimal FDM process parameters. In other study of Kim and Shin [38], the effect of moisture and temperature on the parts prepared through FDM process and injection molding process had been investigated. Many FDM printed parts used in load-carrying application in high moisture and temperature conditions. FDM components followed Fickain diffusion theory for water absorption behaviour, irrespective of the temperature. Temperature rise resulted into increased diffusion rate however absorption rate not affected by it.

In a composite 3D printing, different stacking sequence exhibit different results. Charpy impact test and three point bending test normally conducted to check impact response and flexural behaviour of different stacking of composite. Caminero et al. [39] investigated the effect of stacking sequence of composite. Due to pseudo-ductile behaviour of angle-ply laminate, under impact loading were presented by author. Sugavaneswaran et al. [40] experimentally investigated the elastic modulus of parts printed by using polyjet 3D printers. Normally strength and stiffness of polyjet 3DP parts is typically less and have limitations to use in engineering applications. To overcome this limitations, author has explored new methodology based on multi materials as reinforcement. Addition of reinforcement result in enhancement of elastic modulus in uni-axial tensile test and fracture tests.

Lee et al. [38] deliberate the effect of build direction on mechanical characteristics of 3D printed parts. Experimentation shown that FDM parts had higher compressive strength than other AM processed parts but weaker as compare to traditional manufacturing methods. Espin et el. [20] studied the mechanical characterization of polycarbonate parts. Selection of proper orientation is important criteria when the yield strength is exceeded. If longest contour aligned to the direction of tensile force, it results in greater tensile stresses. Summary of the literature survey based on process parameters has been tabulated in Table 1.

### 3.2 Materials for FDM process

Mechanical properties of RP materials show the phenomenon of anisotropy. The results of anisotropy investigations are presented by various researchers [42]. Present section has been focused on the available material range in AM and their respective properties. Common materials which are being used in FDM are polyoxymethylene (POM), polyamide (PA), polypropylene (PP), nylon 66, Polyether-Ether-Ketone (PEEK), Acrylonitrile Butadiene Styrene (ABS) etc. With these materials, reinforcements like carbon fiber, glass fiber and metal fibers are used. And sometimes dry lubrication films of molybdenum di-sulphide, boron nitride, graphite flakes and poly tetra fluoro-ethylene (PTFE) are used to strengthen the base material [42]–[45]. Ultimate tensile strength of various material at various raster angle is summarized in Table 2. Table 3 is the summery of the some off the standard material that used in FDM AM system. Along with above materials, other materials like polycarbonate (PC) [16], [20], TPA and Nylon 6/6 filament also used in FDM 3D printers.

### 3.3 Inference from literature survey

This approach of manufacturing known as layer by layer manufacturing, has a great potential and applicability in various fields. Key highlights from the understanding of various AM systems are as follows:

1. Liquid based and powder based systems are bulky and costly as compared to solid based system due to use of laser, lens and scanning system. Photo-polymerization consumes less energy but generate fumes which is hazardous and so required a closed environment.
2. Some replacement are available to laser system which are helpful to reduce the cost of liquid based AM systems.
3. In powder based AM system, sintering process used to convert powder into solid object. With the use of high power laser system, metallic powder can be processed in SLS system to create functional prototypes.
4. Among the three classes of AM system, fused deposition modeling stands intermediate applicability. Extruder of FDM system has capability to deal with number of polymer category materials.
5. Efficiency of the FDM system depends on number of factors like environmental factors, material characteristics, machine parameters and working parameters.
6. Due large number of parameters, FDM process become complicated to handle and many researchers considered very few for optimization.
7. Various process parameters effects the overall efficiency of the FDM printed object especially raster angle, part orientation and layer thickness
8. Mechanical strength of FDM printed objects can be enhance by selecting optimum values of process parameters.
9. Wide range of materials available for FDM printers but most of these materials are polymer family which results in less strength as compare to metals. This restricts the use of FDM printed object to demonstration purpose only.
10. Above limitation can be overcome by hybridization i.e. composite structuring.
11. PLA and ABS are widely used by researchers due to good mechanical properties.
12. PEEK and ABS-P500 are biocompatible properties and hence suitable to use in biomedical applications.

4. Conclusion
FDM is widely used 3D printing technique whereas strength of printed parts is poor as compared to powder based additive manufacturing. Enhancement of mechanical characteristics is prime requirement in FDM process. Some deduction has been identified from the review are as follows:
- To improve part quality and mechanical properties FDM printed parts, it necessary to understand correlation between thermo-mechanical properties and process parameters. Thus, development of new mathematical approach is required.
- Different process parameters have significant effect on the performance of FDM system. Most of the researchers considered raster angle, part orientation and layer thickness as influencing parameter. But large number of other parameters where neglected and can be consider for future work.
- The FDM extruder able to deal with different kinds of materials such as ABS, PC-ABS, ABS-P400, ABS-P500, nylon, PLA, HIPS and PEEK. Most of researchers used ABS due to ease of availability and certain mechanical properties. Material combinations i.e. composite materials can be used to enhance mechanical properties of the fabricated parts.
- Very few work has been carried out on biocompatible materials such as ABS-P500 and PEEK.
- Many researchers focused on identification of mechanical characteristics such as tensile, compressive and flexural strength of specific materials. No work has been carried out on identification of tribological properties which are important to identify in case of fabrication of function prototypes.
- No work has been carried out on surface modification/engineering of additively fabricated parts.

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