A Review and Reflection on Part Quality Improvement of Fused Deposition Modelled Parts

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Abstract. Fused deposition modelling (FDM) is an extrusion based additive manufacturing process which fabricates the part by extruding semi-molten thermoplastic material through a small nozzle in a machine platform. The material is deposited layer over layer and the part is fabricated following the bottom up approach. The process can build any complex part geometry in very less time without any tooling problem. Despite of having numerous advantages, fused deposition modelled part’s performance is poorer when measured in terms of part qualities like dimensional accuracy, surface roughness and mechanical strength. Considering the domestic and industrial usage of FDM technology various researchers have contributed their effort in improvement of these part qualities prior to its application. The present study is headed towards reviewing their efforts and reflecting the techniques used for optimization of FDM part qualities.

1. Introduction
Fused deposition modelling (FDM) is an extruded based additive manufacturing processes (AM) used to build parts of any complicated geometry in least possible time without any part specific tooling and process planning requirements directly from the part digital information [1]. For part fabrication in FDM bottom up approach is used where support material is first deposited and then parent material is deposited in a layerwise fashion in accordance with layer thickness decided. The materials used are thermoplastics like ABS (acrylonitrile butadiene styrene), PC (polycarbonate), ABSi (high impact grade of ABS) and PC-ABS etc. FDM can create parts with good thermal and chemical resistance and excellent strength-to-weight ratios [2]. For part having hanging structures FDM also uses support materials. Water soluble support are used for ABS, ABSi and PC-ABS and breakaway support are for PC and PC-ISO (BASS™). Layer thicknesses used for part fabrication are 0.127mm, 0.178mm and 0.254mm [3]. The different areas of application include automobiles (nozzles, gearbox), medical (implant models, surgical simulations), pattern for investment casting and etc.

Process chain of part fabrication is explained as follows:
Step1: CAD model creation - 3D CAD model of part is made using any suitable CAD software. The requirement of CAD model is that it must be water/air tight. In this respect solid models are most
suitable whereas blending of surface patches in 3D surface models may create minute punctures which need to be detected and rectified.

Step 2: Translation of CAD model to STL file format- CAD models in their native format are converted to machine acceptable format, which commonly is stereolithography (STL) file. A STL file defines the surface of a 3-D object in terms of triangular elements. As STL file approximate the actual CAD model therefore number and size of triangular facet must be optimal balance between size, accuracy and processing time. The common errors in STL format are non-manifold facets, cracks, incorrect normal, overlapping facets and redundancy of information etc. and hence need to be detected and rectified using suitable algorithms before processing for AM part fabrication [4]. STL file is transferred to AM processing software.

Step 3: Preprocessing- Each AM machine manufacturer supplies own pre-processing software like Insight™ for FDM. Here, first layer thickness and suitable orientation is decided mainly on the basis of volume of support material required, part material requirement, build time, shrinkage, distortion, surface quality, material cost etc. The requirement of support structure at different part location and different plane is then decided. Supports are geometrically specific and useful for gentle features such as overhangs and internal cavities and also thin-walled sections. Depending on the build orientation and layer thickness selected, STL model is sliced and generates the tool path for each layer. The tool path is generated based on the layer deposition strategy adopted by user and defined in part processing software. The data generated is then changed to SML (Stratasys machine language) format and sent to hardware of FDM for part fabrication.

Step 4: Part Fabrication - The schematic of machine hardware is shown in Fig.1. The support material and part forming ABS material in the form of flexible strand or filament (diameter ~ 1.80 mm) is supplied from the individual canisters located at the bottom of the machine. There are two pairs of rollers each for model and support material. First pair is at the bottom of machine near the canister and other pair is at the top near the nozzle entrance. Bottom rollers grip the material from canister and by their rolling motion advances it towards the nozzle head. Rollers near the nozzle head will guide the material inside the nozzle entrance and this advancing material will provide the extrusion pressure to extrude out the heated viscous material from nozzle exit. Material is heated inside the nozzle to the temperature which is above the glass transition temperature (~110°C) of ABS material.

![Figure 1 Schematic diagram of fused deposition modeling](image)

The material in viscous state is then deposited over the table or previously deposited layer by the X-Y motion of nozzle head. For each layer nozzle head will move in two stages. In first stage, profile of
layer defining the layer boundary is deposited (known as contour deposition) for good surface finish and dimensional accuracy and after that material inside the contour is deposited by controlling motion of deposition nozzle in two stages. In first stage nozzle is moved back and forth to deposit the material equals to the selected width known as raster width and geometry generated is called raster. In second motion nozzle head is incremented by fix distance equal to raster width or some time user defined additional gap is also used between two raster known air gap. The inclination of raster in particular layer with respect to table X-axis is user defined raster angle and to compensate for anisotropy will alter by certain fix angle generally 90° between two successive layers. Material is extruded from the nozzle in temperature control environment and will bound with previously deposited material by fusion bonding principal and solidifies. The platform is then lowered in Z direction by a distance equal to layer thickness choosen for part fabrication. After this entire process of layer deposition continues till the part is finished. Two sets of nozzles are used: one for part material deposition and other for support material deposition. These two nozzles will not deposit material simultaneously. Once one nozzle is depositing a material other will be vertically offset to prevent rubbing on deposited material.

Step 5: Post processing - Once the part build is finished it is taken out from the chamber and support material is removed by hand or some time by vibrations generated in ultrasonic bath.

FDM techniques are capable of fabricating part of any complex geometry in very less time without any tooling problem. As shown in Fig. 2 the performance measures of FDM process depends on dimensional accuracy, surface roughness, mechanical strength, build time, material properties and post-processing.

2. Dimensional Accuracy
In a process to evaluate the manufacturing accuracy of various AM machines ISO-ANSI (International Organization for Standardization- American National Standards Institute) standards concluded that part quality was mostly affected by process parameter settings [5]. Xu et al. used a standard part to study the accuracy of four different AM processes namely SLA, SLS, FDM, and LOM [6]. It was noticed that SLA process shows the best dimensional accuracy in whole whereas SLA and LOM shows best results for round and cylindrical features. It was also noticed that FDM produces
the worst result. Comparison between the dimensional accuracy and surface details of three prototype models with a 3D STL (standard template library) image: FDM model using ABS (acrylonitrile butadiene styrene), polyjet model using a clear resin and 3-dimensional printing (3DP) using a composite material was presented by Murugasen et al. [7]. Measurement at various points shows that dimensions of the model created by polyjet were closest to the 3D STL virtual image and is followed by the 3DP model and then by FDM. Nizam et al. [8] made a skull model using stereolitography and investigated on its dimensional accuracy. The degree of accuracy produced by SLA system made it reasonable in clinical applications like dental surgery for surgical treatment planning. Errors also arises due to process related attributes like material properties, material feed uniformity, machine path control accuracy, tool scan speed uniformity, platform control accuracy and part thermal shrinkage and distortion [9]. Effect of process parameters on shrinkage characteristics in SLS process shows that shrinkage increases with increase in the scanning speed and hatch spacing percentage however it decreases with increasing layer thickness, laser power, part bed temperature and delay time [10]. Based on the numerical analysis of the stereolithographic process by Campanelli et al. it was found that maximum value of hatch overcure (HO) and border overcure (BO) are used for better part accuracy at higher layer thickness [11]. For low layer thickness is medium levels for HO and BO is however proposed. Effect of post-curing and laser manufacturing parameters on the properties of the photosensitive resin in SLA process concludes that anisotropic properties was shown by uncured and partially cured resins trapped within the part [12]. Variation in linear dimensional behaviour was found to be dependent on the degree of cure influenced by the laser’s power, resin’s photosensitivity characteristics and other parameters. Main factor affecting the dimensional accuracy of high-resolution SLA parts are hatching space, coefficient of the resin’s shrinkage compensation and the interaction between the scanning speed and hatch spacing.

Investigation done by Byun and Lee shows that part orientation in additive manufacturing processes is highly influenced by part strength, dimensional accuracy, surface finish, part build time and cost [14]. Lee et al. through their experimental work also propose that dimensional accuracy of FDM processed part was mostly influenced by their processing parameters [15]. Wang et al. found that dimensional accuracy was seriously affected by build orientation and depositing thickness. Masood et al. [17] proposed the optimum build orientation for different part geometries. Nancharaiiah et al. [18] in their study concluded that layer thickness and air gap has most serious effect on dimensional accuracy of FDM parts. An experimental relation between dimensional error and deformation of FDM part was proposed by Zhang and Peng [19]. Optimal process parameter values for minimizing dimensional error are also proposed. Effect of five process parameters namely part orientation, road width, layer thickness, air gap and raster angle on dimensional accuracy of FDM ABS P400 was studied by Sood et al. [20]. It was observed that part dimension shrink along length, width and thickness of the fabricated part was above the chosen value. They observed that optimum process parameters were different for each quality criterion thus optimization of processing parameters was done. To reduce the deviations in dimensions they recommended the factor setting of 0.178 mm layer thickness, part orientation of 0º, raster angle of 0º, road width of 0.4564 mm and air gap of 0.008. Study by pennington et al. identified that part size, location and temperature of work envelop had a greater effect on the dimensional accuracy of FDM part [21]. For the dimensional improvement of part manufactured using FDM process optimization of FDM processing parameters is suggested by Noriega et al [22]. Improvements in external as well as internal dimensions were observed. Accuracy of fabricating cylindrical shapes of part in FDM was investigated by Bakar et al. [23]. They have observed a significant deviation in radial direction and proposed that due to constraint in movement of deposition head FDM machine is less accurate for fabricating cylindrical part. Sahu et al. [24] stated that among the various factors affecting parts dimensional accuracy in FDM process change in part orientation has the greatest effect among the all. They also propose the optimal levels of process parameters for minimum change in length, width and thickness. To reduce the dimensional variation Kumar et al. modified the part geometry by adding the calculated standard deviation for the part measured with a CMM [25].
3. Surface Roughness

Surface roughness of part manufactured with AM techniques is very important specially when they come in contact with other elements. In this direction Perez et al. [26, 27] gave a theoretical model for calculating the roughness of part fabricated by SLA-350 apparatus. For achieving better surface finish modification of layer thickness as a function of the slope of the exterior profile is recommended. Kim and Lee [28] uses a population based genetic algorithm method for calculation of surface roughness of parts fabricated by SLA. Developed algorithm can effectively predict the roughness of various part geometries however the model requires larger time for part fabrication though the post processing time was reduced. Combination of coating and grinding processes technology is proposed by Ahn and Lee [29] for enhancing the surface finish of SLA parts. Paraffin wax was used as coating material whereas grinding materials are pulp. They found that by grinding the coating wax up to the boundary of the part the surface smoothness can be improved. Surface finish of ice parts built by the rapid freeze prototyping (RFP) process shows that water deposition rate, scanning speed and contact angle are the main parameter affecting the part finish. Paul and Voorakarnam [31] also proposed a model for predicting the roughness behaviour of laminated object manufacturing (LOM) built parts. Developed model was capable of accurately predicting the roughness of part having reasonable surface roughness. Rapid manufacturing of metal tooling by additive manufacturing processes is also investigated by Shan et al. [32]. They proposed that RP pattern, surface roughness, refractory grading, metal and mould temperatures are important factor affecting surface roughness of metal tools. Refractory grade is suggested to obtain better surface finish in metal part. Wang et al. [33] measured the surface roughness and porosity of Cu, Fe and Ni-based laser-sintered material. They concluded that the build direction has more roughness than the surface parallel to the building direction. Effect of laser power, scan speed, scan spacing, and layer thickness on surface roughness laser sintered metal parts were also investigated by Simchi et al. [34]. Improvement in surface quality after post processing of laser sintered part was observed. Increase in surface roughness with increase in laser power and decrease in surface roughness with increase in scanning speed is also proposed [35].

In a FDM process, parameters like part build orientation, raster to raster air gap, model temperature, layer thickness and raster width and layer thickness are most significant factor affecting part surface roughness [36]. Effect of various process parameters on FDM part quality was investigated by Anitha et al. [37]. It was observed that in comparison to road width and speed of deposition quality of parts is significantly affected by layer thickness. Through correlation analysis it has been established that layer thickness and surface roughness varies inversely. Nanchanaiyah et al. [18] proposed that selection of low layer thickness and low air gap can improve the part surface roughness because it reduced the void formations between layers. Surface roughness on ABS400 polymer was investigated by Horvath et al. [38]. They propose that layer thickness and model temperature are the significant factor affecting the surface roughness. In their study model temperature of 274 ºC and layer thickness of 0.1778 mm shows minimum surface roughness. Effect of slice thickness, road width and diameter of nozzle tip on FDM part were investigated by Galantuici et al. [39]. They observed that selected slice thickness and the road width are crucial parameters while the tip diameter of nozzle has little significance for surfaces running either parallel or perpendicular to the build direction. Mahapatra et al. [40] combines the Bayesian regularization-based levenberg-marquardt neural model with BFOA for improving surface finish of ABS P400 part fabricated by FDM Vantage SE machine. While analysing the effect of process parameter on part finish they concluded that raster width is the most important parameter affecting the surface finish at the top face of part. Part orientation and layer thickness are observed as significant factors for reduction of surface roughness at bottom and side faces. Bordoni et al. [41] also suggested that layer thickness and part orientation were the main factors influencing the average surface of the part manufactured by FDM. To predict the surface roughness of part manufactured by FDM a 3D roughness profile model was suggested by Boschetto et al. [42]. Roughness was found to be affected by raster orientation and it was proposed that model can very well predict the best raster orientation which will provide the optimal surface quality Durgun and Ertan [43] also shows that parts built by FDM with different part orientations have a strong effect on the surface roughness. Pandey et al. [44] studied the effect of staircase effect on surface finish of FDM part and for reducing this staircase effect and improving part
finish they proposed a hybrid machine combining FDM and hot cutter machining. Finishing operation in their method however is time consuming for complex part geometries. Allen and Dutta [45] proposed a method for automatically calculating the support structure for the part in layer manufacturing and then deciding the best orientation. In their method they have selected different part orientations and for each part orientation an approximation of required support structure was made. Centre of mass for each object in particular orientation was found. Based on the stability of object and minimum surface area of contact between support structure and the object best orientation is selected from the different orientation chosen. To improve the surface finish of part built by FDM process integration of FDM and BF (barrel finishing) methods are proposed by Boschetto et al. [46]. In this method first FDM parts are produced and then for post processing is done in a rotating barrel machine. In a BF process FDM part, abrasive media and water are put in a rotating barrel and given specific speed which results in finishing of FDM part. To improve the surface quality of parts fabricated from acrylonitrile butadiene styrene materials chemical finishing method was suggested as an alternative by Perco et al. [47]. Chemical solution of 90% dimethyl ketone and 10% water was used. Significant improvement in surface finish was observed. They also proposed that chemical treatment is economic, fast and easy to use. More research on use of chemical treatment for improving surface roughness is also given by same authors [48].

4. Mechanical Strength
An important requirement for AM processes is that fabricated part must have adequate mechanical strength. This becomes more important when these parts are used in applications which produce intensive machining conditions affecting its shape and integrity. Effect of process parameters on strength of SLA parts was investigated by Chockalingam et al. [49]. They proposed that strength of the part is affected by layer thickness, part orientation and post curing time where part orientation was found to have the most significant effect among all. Establishment of process model for part strength of stereolithography parts was also presented by above authors [50]. In their study effect of processing parameters on the strength of parts made with CIBA Tool 5530 in SLA 5000 machine was also performed. It was observed that strength of part was significantly affected by layer thickness. They proposed that before part fabrication by machine an estimation of part strength can be accurately predicted by developed model for any set of parameters. Pandey et al. [51] observed that in SLS process the time difference for laser exposure between any two adjacent points on successive scanning lines depends on part build orientation. An algorithm was thus proposed to find out optimum part build orientation which can provide improved tensile strength. For laser additive manufactured (LAM) part Emmelmann et al. [52] suggested that maximum yield strength and maximum tensile strength of part was obtained at a part orientation of 0˚ with respect to the building plane whereas part orientation of 90˚ shows minimum yield and tensile strength. The above researchers also proposed that failure of LAM part is mainly due to generation of residual stresses [52]. They suggested two main causes for development of residual stresses. First reason is variation in the materials microstructure due to melting and solidification of powder and second reason is change property of already solidified layer due to shrinkage at the top layer exposed to laser.

Lee et al. [53] performed the comparative study on strength of cylindrical part fabricated by three different processes namely FDM, 3D printer and nano composite deposition (NCDS). It was proposed that compressive strength of axial FDM part was 11.6% higher than strength of transverse FDM parts. Diagonal specimen has maximum compressive strength when compared to axial specimen in 3D printing however NCDS parts were noted to have 23.6% higher compressive strength than transverse specimen. It was concluded that parts built by NCDS are severely affected by the build direction. In a FDM process where part material is extruded from nozzle tip and solidified in a chamber at constant temperature volumetric shrinkage takes place resulting in a weak interlayer bonding, high porosity which reduces part strength [54]. Development of inner stresses due to uneven heating and cooling leads to inter layer and intra layer deformation which appears as crack, de-lamination and even part fabrication failure [55]. Deformation in part is mainly caused due to accumulation of residual stresses at the bottom surface of the part during fabrication and which increases with the increase in stacking section length [56]. In a FDM process, extruded material is cooled from glass transition temperature to
chamber temperature resulting in the development of inner stresses which cause inter and intra-layer distortion in the form of cracking and delamination or even part fabrication failure. Thus material with linear shrinkage rate and lower glass transition temperature is preferred [57]. Effect of process parameters on the tensile strength and compressive strength of the FDM parts was experimentally investigated by Ahn et al. [58]. They concluded that by using optimum process parameters combination the tensile strength and the compressive strength of the ABS part were in the ranges of 65% - 72% and 80% - 90% respectively. Ang et al. [59] proposed that air gap has the largest effect on the porosity and mechanical properties of the part fabricated by FDM. Wang et al. [60] proposed that tensile strength of FDM part was significantly higher when samples are fabricated Z-direction orientation. It was also reported that when samples are fabricated with orientation perpendicular to the generated layer it will have the least strength. Sood et al. [61] investigated the compressive strength of FDM printed parts under various process parameters (layer thickness, air gap, raster width, raster angle, and build orientation). It was observed that by increasing the layer thickness less number of layers is deposited which reduces the residual stress and deformation in the part and improved part strength. It was also concluded that larger raster length deposited by small raster angle would increase residual stress and deformation and hence affect the bonding strength. It was proposed that thick raster and zero air gaps improved the mechanical properties. The effect of various process variables such as build orientation, raster angle, raster width, and air gap on tensile strength of the ABS processed parts have been analyzed by Onwubolu and Rayegani [62]. For better part strength they also proposed low value of air gap and build orientation whereas use of higher raster angle was recommended. Durgun and Ertan [43] present the effect of part orientations and raster angles on tensile strength and flexural strength of FDM fabricated part. Their study also demonstrates that part orientation has a strong effect on the surface roughness and mechanical performance of FDM part and effect of raster angle is least. Lanzotti et al. [63] investigated the effect of process parameters (layer thickness, infill orientation and the number of shell perimeters) on the ultimate tensile strength of FDM polylactic acid printed parts and suggested that optimal parameter settings can be used to optimize the ultimate tensile strength. Masood et al. [64] experimentally investigated the effects of the FDM process parameters on the tensile properties of polycarbonate (PC) FDM parts. It was observed that the tensile strength of PC part is highly depended upon build style. They have proposed the use of solid normal build style because it will fill the part completely and produce denser part. They also concluded that FDM fabricated PC material has good tensile strength ranging from 70% to 80% of the injection molded PC parts. Percoco et al. [47] investigated the influences of the chemical treatment on the compressive strength and mechanical behaviour of treated FDM parts. They also propose that the compressive strength of part increases with the increase of raster width. It was concluded that the immersion up to 300 s could be used to decrease the roughness by 90% making mechanical properties better.

5. Conclusions
Fused deposition modelling (FDM) is one of the fastest growing extrusion based additive manufacturing process. Quality of FDM parts depends on various factors namely materials, dimensional accuracy, surface roughness, mechanical strength and post processing. Literature survey reveals that among the various factors affecting FDM part performance (depicted in Fig. 2) vital factors are dimensional accuracy, surface roughness and mechanical strength. Study undertaken presents the reflection on important studies undertaken in the field of dimensional accuracy, surface roughness and mechanical strength of FDM parts. It was observed that these part qualities of FDM parts are directly by the process parameters selected for part fabrication. Important process parameters of FDM are raster angle, raster width, air gap, build time, build orientation and slicing thickness selected. Parametric optimization of FDM process is thus suggested to improve the part quality of FDM process.

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