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Optimization of fused deposition modeling process parameters: a review of current research and future prospects

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Abstract Fused deposition modeling (FDM) is one of the most popular additive manufacturing technologies for various engineering applications. FDM process has been introduced commercially in early 1990s by Stratasys Inc., USA. The quality of FDM processed parts mainly depends on careful selection of process variables. Thus, identification of the FDM process parameters that significantly affect the quality of FDM processed parts is important. In recent years, researchers have explored a number of ways to improve the mechanical properties and part quality using various experimental design techniques and concepts. This article aims to review the research carried out so far in determining and optimizing the process parameters of the FDM process. Several statistical designs of experiments and optimization techniques used for the determination of optimum process parameters have been examined. The trends for future FDM research in this area are described.

Keywords Fused deposition modeling (FDM) · Experimental design · Additive manufacturing · Process parameters · Mechanical properties · Part quality

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1 Introduction

Additive manufacturing technology is an advanced manufacturing technology used for fabricating parts layer by layer directly from a computer aided design (CAD) data file. The process builds objects by adding material in a layer by layer fashion to create a three-dimensional (3D) part, offering the benefit to produce any complex parts with shorter cycle time and lower cost compared to traditional manufacturing process. Additive manufacturing technology is widely used in engineering for customized products, functional models, pre-surgical models and conceptual models. This technology is finding its applications in many fields of engineering and industry, such as aircraft, dental restorations, medical implants and automotive products. With increased competition in the world economy, designers and production engineers face the challenge of producing products more quickly than ever to meet customer requirements and achieve competitive edge. Additive manufacturing process offers an efficient technique of building complicated geometry to shorten the design and production cycle time at the lowest cost due to the absence of any tooling needs [1–6]. There are many commercial additive manufacturing systems available in the market such as fused deposition modeling (FDM), direct metal deposition (DMD), 3D printing, selective laser sintering (SLS), inkjet modeling (IJM) and stereo-lithography (SLA). These systems differ in the manner of building layers and in the types of materials that can be fabricated by these processes safely.

FDM has been widely used in additive manufacturing technology that provides functional prototypes in various thermoplastics due to its ability to produce complex geometrical parts neatly and safely in an office-friendly environment. FDM was developed by Stratasys Inc. in

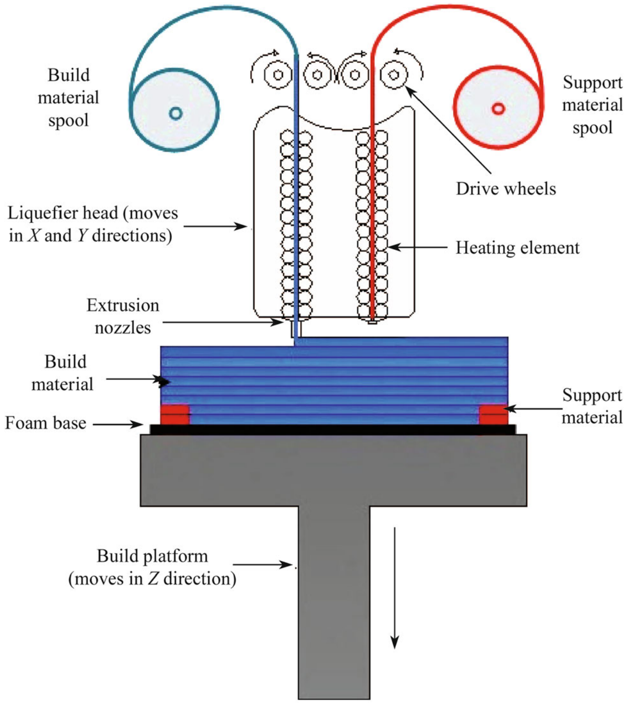

Fig. 1 Principle of FDM process

USA in 1990s [7–11]. FDM is now commonly used for modeling, prototyping, and production applications. As shown in Fig. 1, in this process, the material is melted into liquid state in a liquefier head and then selectively deposited through a nozzle that traces the parts cross sectional geometry to produce 3D parts directly from a CAD model in a layer by layer manner. A wide range of materials are available for this manufacturing process such as acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and PC-ABS blend.

This paper presents a comprehensive review of FDM process parameter optimization involving statistical design of experiments (DOEs) and optimization techniques, and identifies several research gaps where further research and development work can be directed to make this technology deliver products with higher accuracy, better quality and desired properties.

2 FDM process parameters

Nowadays, the additive manufacturing processes including FDM process are required to deliver superior part quality, high productivity rate, safety, low manufacturing cost, and short lead time. In order to meet the customer needs and satisfaction, the additive manufacturing process conditions must be established for each application. The key success of the additive manufacturing process depends upon the proper selection of process parameters. Determination of the optimum process conditions is an important task for production engineers. It plays an important role to ensure quality of products, improve dimensional precision, avoid unacceptable wastes and large amount of scraps, enhance productivity rates and reduce production time and cost. FDM is a complex process that exhibits much difficulty in determining optimal parameters due to the presence of a large number of conflicting parameters that will influence the part quality and material properties. The part quality and mechanical properties of fabricated part can be attributed to proper selection of process parameters [12, 13]. Figure 2 shows all the process variables that need to be studied and optimized in FDM process. Several statistical optimization techniques have been successfully used for the optimization of process conditions of FDM rapid prototyping technology.

Figure 3 shows the meanings of some FDM process parameters. Some main parameters are also described as follows.

(i) Build orientation refers to the way in which the part is oriented inside the build platform with respect to X, Y, Z axes, as shown in Fig. 3a.
(ii) Layer thickness is the thickness of layer deposited by nozzle tip, as shown in Fig. 3b. The value of layer thickness depends on the material and tip size.
(iii) Air gap refers to the gap between adjacent raster tool paths on the same layer, as shown in Fig. 3c.
(iv) Raster angle refers to the angle of the raster pattern with respect to the X axis on the bottom part layer. Specifying the raster angle is very important in parts that have small curves. The typical allowed raster angles are from 0° to 90°.
(v) Raster width is the width of the material bead used for rasters. Larger value of raster width will build a part with a stronger interior. Smaller value will require less production time and material. The value of raster width varies based on nozzle tip size.

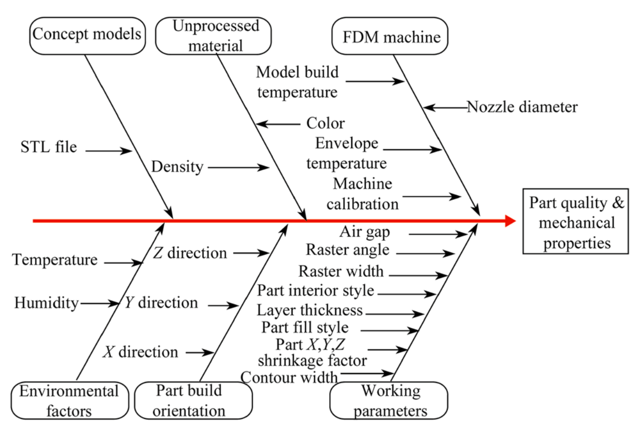

Fig. 2 Cause and effect diagram of FDM process parameters

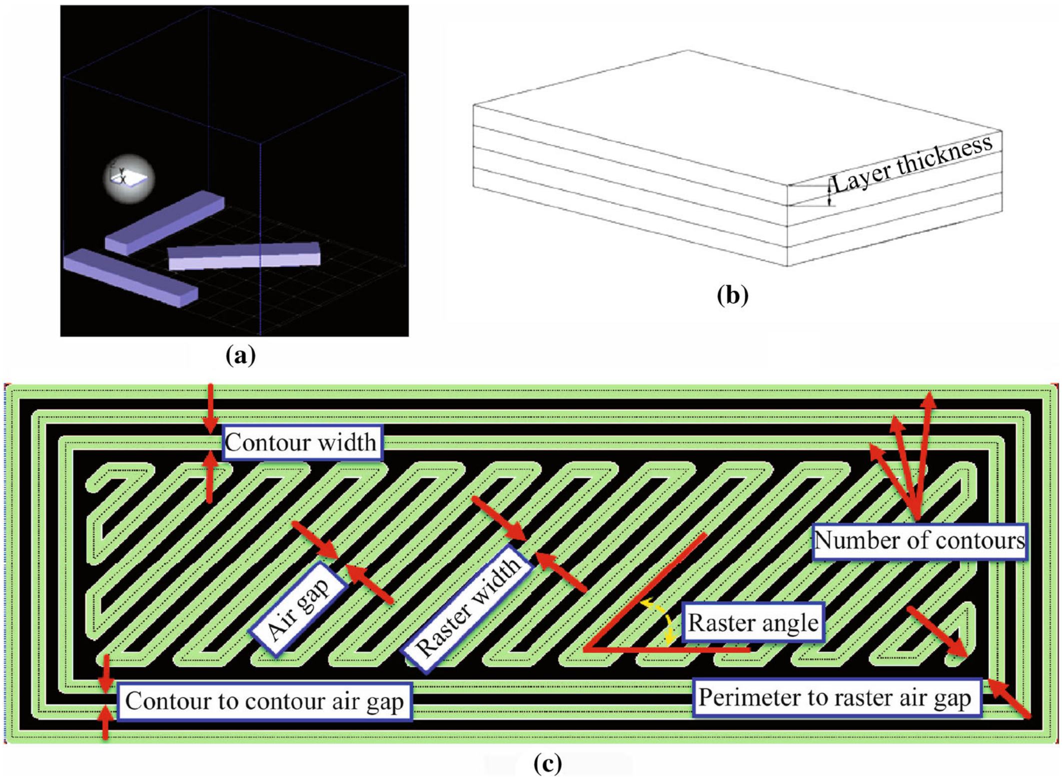

Fig. 3 **a** Build orientations, **b** layer thickness, and **c** FDM tool path parameters

(vi) Contour width refers to the width of the contour tool path that surrounds the part curves.
(vii) The number of contours to build around all outer and inner part curves is shown in Fig. 3c. Additional contours may improve perimeter part walls.
(viii) Contour to contour air gap refers to the gap between contours when the part fill style is set to multiple contours.
(ix) Perimeter to raster air gap refers to gap between the inner most contour and the edge of the raster fill inside of the contour.

Build style refers to the way in which the part is filled. It controls the density of the part. There are three types of build styles.

(i) "Solid normal" fills the interior part completely. It will build a part with a stronger interior.
(ii) "Sparse" minimizes the material volume and build time by leaving gaps. It utilizes a uni-directional raster.
(iii) "Sparse double dense" reduces the material volume and build time. It utilizes a crosshatch raster pattern.

Some other parameters are shown as follows.

(i) Visible surface is used to maintain part appearance while allowing for a coarser, faster fill by normal rasters or fine rasters.
(ii) Part fill style determines the fill tool path of the bead to build the solid model.
(iii) Part Z shrinkage factor refers to the shrinkage factor applied in the Z axis.
(iv) Part X–Y shrinkage factor refers to the shrinkage factor applied in the X and Y axes.

Support style refers to the portions of a model that extend outward to prevent the part from collapsing during the building process. It is of four types.

(i) "Basic" is the standard raster tool path support structure. It supports all part features with small support raster curves.
(ii) "Sparse" reduces the amount of support material volume. It uses less amount of material than basic support.
(iii) "Surround" fills the surround small features or small parts. It is used for all parts.
(iv) "Break-away" is similar to "Sparse", but it contains discrete boxes and it is easier to remove than other three types of support structures.

3 Research on FDM process optimization

FDM process conditions play an important role in improving surface roughness, dimensional accuracy, mechanical properties, material behavior and build time. Critical process parameters that affect the quality of processed part have been discussed. There has been extensive research on this topic focusing on experimental results and process optimization. Most of the researches on FDM process parameters have been directed toward optimizing process parameters to improve the surface finish, dimensional accuracy and mechanical properties for ABS processed parts. Many researchers have suggested using appropriate statistical designs and optimization techniques to study the effects of process parameters on FDM processed parts. In the following subsections, research on each quality characteristic is reviewed in detail.

3.1 Surface roughness

Anitha et al. [14] investigated the effects of some important FDM process parameters on surface roughness of ABS prototype. The Taguchi's design matrix, signal to noise ratio (S/N) and analysis of variance (ANOVA) were used in this study. Three process parameters including layer thickness, road width and speed of deposition were considered. This study revealed that the factor having the most important influence on the surface roughness was the layer thickness compared to road width and speed. It was also revealed that there was inverse relation between layer thickness and surface roughness.

Nancharaiah et al. [15] studied the influences of process parameters such as layer thickness, road width, raster angle and air gap on the surface finish of FDM processed ABS part through Taguchi method and ANOVA technique. It was seen that surface roughness could be improved by using lower value of layer thickness and air gap because it reduced the voids between layers. The weakness of this approach [14, 15] lies in only determining the best combination of process parameters. It cannot be used to determine the final optimum process conditions particularly in cases of multi-quality optimization.

Thrimurthulu et al. [16] used real coded genetic algorithm (GA) to develop an analytical model to predict the optimum part orientation for surface roughness. The prediction of the developed model was validated and it was in good agreement with the result published earlier. This study concluded that the developed model could be used to predict the optimum part orientation for any complex freeform surfaces. However, this developed model has the limitation that it can only predict build orientation but other critical process parameters cannot be predicted by this model.

Horvath et al. [17] conducted a study for improvement of surface roughness on ABS400 polymer materials using factorial design. In this study, only three process parameters namely model temperature, layer thickness and part fill style were selected. The results showed that the layer thickness played an important role in minimizing surface roughness, where the minimum value of surface roughness of 5.83 μm was obtained when the model temperature was 274 °C with the layer thickness of 0.1778 mm and the fill style of fine raster's. They concluded that high value of model temperature was preferred as it led to smooth surface.

Wang et al. [18] used a statistical optimization method to investigate the effects of control parameters such as layer thickness, deposition style, support style, and deposition orientations on the surface roughness by integrating the Taguchi method with the gray relational analysis. It was concluded that by using the optimum factor settings, the surface roughness was improved by 62.27%. This study revealed that optimal parameter combinations of surface roughness were obtained with less number of experimentations using Taguchi method compared to full factorial design which yielded similar results.

3.2 Dimensional accuracy

Wang et al. [18] also pointed out that dimensional accuracy of fabricated part depended on build orientation and depositing thickness. The differences in dimensional accuracy in the different building directions were the results of different deposition patterns.

Sood et al. [19] studied the influences of five process parameters including part orientation, road width, layer thickness, air gap and raster angle on dimensional accuracy of FDM fabricated ABSP400 part using gray Taguchi method. They pointed out that there was shrinkage along the length, width and diameter of the hole of the fabricated part as the dimensions were less or more than the designed value. However, thickness of the fabricated part was above the desired value. It was concluded that to reduce the deviation between fabricated part dimension and CAD model dimension, layer thickness of 0.178 mm, part orientation of 0°, raster angle of 0°, road width of 0.4564 mm and air gap of 0.008 mm should be used. In this study, the optimum process parameters were different for each quality criterion, indicating that the optimum process conditions could not be obtained. Therefore, further work has been done by employing gray relational grade (GRD) to convert three responses into one response. In order to predict these three responses more accurately due to their non-linearity, they used artificial neural network (ANN) and fuzzy logic. After all this work, the best parameter combinations were obtained.

Nancharaiah et al. [15] also applied Taguchi method and ANOVA technique to identify the key factors that influenced the dimensional accuracy of deposited ABS parts. The input variables such as layer thickness, road width, raster angle and air gap were considered. They concluded that layer thickness and air gap significantly affected the accuracy of FDM parts. However, in this study, optimum settings of layer thickness, road width, raster angle and air gap in the range were not addressed.

Zhang and Peng [20] established empirical relations between process parameters (wire-width compensation, extrusion velocity, filling velocity, and layer thickness) and dimensional error and deformation of FDM fabricated ABS part using Taguchi method combined with fuzzy comprehensive evaluation. They reported that the optimal process parameter values for dimensional error were: wire-width compensation 0.17 mm, extrusion velocity 20 mm/s, filling velocity 30 mm/s and layer thickness 0.15 mm. In case of deformation, the optimum combinations of the parameters were: wire-width compensation 0.17 mm, extrusion velocity 25 mm/s, filling velocity 20 mm/s and layer thickness 0.30 mm. In this study, other various process parameters were not considered. Only the best combination of the selected process parameters was obtained. Furthermore, if the goal was to minimize both dimensional error and deformation together, the study could not provide a definite answer in terms of global solution to this problem.

In a recent study, Sahu et al. [21] applied Taguchi method to study the main and interaction effects of process variables such as layer thickness, orientation, raster angle, raster width and air gap on part accuracy. In this study, prediction model based on fuzzy logic and Mamdani method was developed to optimize dimensional accuracy. It was concluded that the value of average percentage error of less than 4.5% was obtained from the laboratory experiment which agreed well with the predicted response. However, the use of fuzzy inference system (FIS) requires developing rules. Therefore, it needs appropriate expertise knowledge and experience.

3.3 Material behavior

Lee et al. [22] performed experimental investigation on optimization of rapid prototyping parameters for production of flexible ABS object. They carried out Taguchi method and ANOVA technique considering air gap, raster angle, raster width and layer thickness as parameters. The study concluded that layer thickness, raster angle and air gap were the critical factors in determining the elastic performance of the part. The optimum parameters determined and the results obtained were in a good agreement with the laboratory experiments with error percentage of 0.18%.

Laeng et al. [23] found the effects of air gap, raster angle, raster width and layer thickness on the elasticity performance of ABS material for FDM by using Taguchi method and ANOVA procedure. Based on their study, the optimum combinations of process parameters were obtained for improving overall elasticity performance. However, the optimal settings are restricted to the experimental values only, where, in fact, the optimal settings are not exactly the same as the parameters' values. Thus the optimal parameter settings cannot be obtained using this approach. It can be obtained using response surface methodology (RSM) and empirical optimization techniques.

Zhang and Chou [24] looked at relating process parameters to stress distribution and part distortions. They developed a finite element model to evaluate the stress distribution and part distortions at different deposition conditions. Central composite design (CCD) and ANOVA were used to establish the correlation between process parameters and residual stresses and part distortions in FDM process. Road width, layer thickness, and scan speed were selected as main parameters. It was reported that layer thickness was the key factor that affected the residual stresses and part distortions. The study concluded that the residual stresses and part distortions increased with layer thickness and road width during the deposition stage. The main aspect in this study was that the finite element model developed was in good agreement with the experimental result with a small error. However, a limitation of this study was that a combined parameter setting could not simultaneously satisfy all the objectives.

3.4 Build time

Thrimurthulu et al. [16] also presented a mathematical model to predict and optimize the build time. They considered build orientation as the most significant process variable that affected the build time. From the results, optimum build orientation was obtained using a real coded GA. They compared the predictive capabilities of the models developed with other published works. It was clear that the proposed model was in reasonable agreement with the result published earlier.

In another study, Nancharaiah [25] examined the relationship between process parameters and build time using Taguchi's design matrix $\boldsymbol{L}^9$ orthogonal array and ANOVA technique. It was pointed out that process parameters such as layer thickness and air gap could affect the build time significantly. It was also reported that the layer thickness and air gap contributed 66.57% and 30.77% respectively on the build time. The results also revealed that layer thickness of 0.330 mm, air gap of 0.020 mm and raster angle of 30° were the optimum parameters to reduce the build time. Nevertheless, optimum conditions for the objectives were not given.

Kumar and Regalla [26] applied 2^5 full factorial design to analyze the influence of each process parameter, such as layer thickness, raster angle, orientation, contour width and part raster width on support material volume and build time of FDM part. It was experimentally reported that the layer thickness and build orientation were important factors in the minimization of the build time. However, the study did not focus on the optimum process settings that minimize the build time and support material volume.

3.5 Mechanical properties

3.5.1 Static mechanical properties

Ahn et al. [27] experimentally investigated the effects of FDM parameters and build orientation on the tensile strength and compressive strength of the ABS parts processed by FDM. Varied parameters in the experiments were air gap, road width, model temperature, material color and build orientation. For the purpose of determining the effects of the process parameters on the mechanical properties, a 2^5 full factorial design was used. They concluded that by using optimum process parameters, 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. [28] revealed that the mechanical properties and porosity of ABS manufactured parts were mostly influenced by process conditions such as air gap, raster width, build orientation, build laydown pattern and build layer. They used 2^5 fractional factorial design to understand the influence of each process variable. They reported that air gap had the largest effect on the porosity and mechanical properties of the scaffolds. Based on their study, multiple regression models were used to check the significant improvement of mechanical properties and porosity. In this work, the effects of some variables on mechanical properties were studied, and determination of optimum settings was not considered.

Wang et al. [18] found that tensile strength of FDM part was significantly higher when testing samples were put in the deposition orientation—*Z* direction. They demonstrated that the worst tensile strength was observed when testing samples were in the direction perpendicular to the layer. The developed model was verified experimentally and the predicted results agreed well with laboratory experiments. However, they obtained the three independent optimum solutions, for the minimum dimensional deviation, the minimum surface roughness, and the maximum tensile strength, respectively. If the dimensional deviation and surface roughness should be as minimum as possible, and at the same time the tensile strength should be maximized, the paper could not provide a conclusive answer and overall solution to this problem.

In a later study, Sood et al. [29] developed a mathematical model to optimize the mechanical properties of FDM parts using the following input variables: layer thickness, build orientation, raster angle, raster width and air gap. CCD and ANOVA were employed. This study concluded that by increasing the layer thickness, less number of layers were required. This reduced residual stress and deformation in the part, and improved part strength through improving part resistance. It was also concluded that small raster angle was not preferred as small raster angle would increase residual stress and deformation, hence it would weaken bonding strength. It was observed that thick raster and zero air gap improved the mechanical properties.

Percoco et al. [30] investigated the influences of the chemical treatment on the compressive strength and mechanical behavior of treated FDM prototypes. This study investigated the effects of three process parameters including raster width, raster angle and immersion time on compressive strength using CCD. The results showed that in terms of untreated specimens (non-finished parts), raster angle had a very low influence on the compression strength. The results also revealed that the compressive strength increased with the increase of raster width. They concluded that the immersion time of up to 300 s could be used to decrease roughness by up to 90%, making mechanical properties better than untreated parts.

The most recent study was published in 2014 by Rayegani and Onwubolu [31]. It was an advanced learning on experimental investigation and optimization of FDM process parameters on tensile strength using full factorial design, group method of data handling (GMDH) and differential evolution (DE). Build orientation, raster angle, raster width and air gap at two levels were considered as parameters. The optimum process parameters were obtained to maximize tensile strength, and the study reported that maximum tensile strength could be obtained when the build orientation was at 0°, raster angle at 50°, with the raster width of 0.2034 mm and negative air gap of −0.0025 mm.

Masood et al. [32] experimentally investigated the effects of the FDM process parameters such as build style, raster width, and raster angle on the tensile properties of PC FDM. They concluded that the highest tensile strength could be obtained when build style was solid normal, raster width was 0.6064 mm and raster angle was 45°. It was also concluded that the tensile strength of PC prototype greatly depended upon build style because the solid normal build style filled the part completely with fully dense raster tool paths. This study also concluded that PC material had good tensile strength ranging from 70% to 80% of the injection molded PC parts.

3.5.2 Dynamic mechanical properties

In addition to static loading conditions, FDM manufactured parts are also subjected to the dynamic and cyclic loading conditions such as in vibrating machinery and transportation applications. Very few studies have been conducted on understanding the behavior of FDM parts subjected to such loading conditions.

Arivazhagan et al. [33] investigated the effects of the FDM process parameters such as build style, raster width, and raster angle on the dynamic mechanical properties of PC processed part. Frequency sweep from 10 Hz to 100 Hz was used at three different isothermal temperatures. It was concluded that solid normal build style with raster angle of 45°, and the raster width of 0.454 mm led to the best dynamic properties than other build styles (double dense and sparse).

In another study, Arivazhagan and Masood [34] presented experimental investigation on dynamic mechanical properties but with ABS part fabricated by FDM. They observed that solid normal build style provided higher modulus than double dense and sparse build styles. It was experimentally reported that with increasing temperature, the loss modulus increased. However, storage modulus and viscosity decreased with the increase of temperature.

Jami et al. [35] experimentally investigated the influences of three different build orientations on high-strain-rate dynamic response of ABS parts manufactured by FDM using a split Hopkinson pressure bar. Three different build orientations, vertical on *X–Y* plane parallel to *Z*-axis, horizontal at 0° to *X*-axis and horizontal at 45° to *X*-axis were considered. From the experimental results, it was demonstrated that the build orientation, which was vertical on *X–Y* plane parallel and horizontal at 45° to *X*-axis resulted in higher modulus of the part. They also found that there was no influence of build orientations on the stress strain responses under quasi-static conditions. However, build part orientation has an effect on dynamic response of the FDM fabricated parts. It was reported that ABS part made by FDM had the ability to be an effective material under quasi-static and high-strain-rate conditions.

However, the limitations of the work in Refs. [32–35] lie in studying the relationships between FDM process variables and mechanical properties of fabricated parts without using scientific methods such as DOE and optimization techniques. The disadvantage of this approach is that it may lead to wrong optimal results because the interactions between factors identifying their importance to the output response and best settings of these variables cannot be determined. Therefore, for practical applications, these interactions and best settings of processing parameters need to be estimated.

4 Results and discussions

After reviewing the published literature, it is clear that optimization of process parameters of FDM additive manufacturing technology is one of the most critical design tasks in quality evaluation indicators for obtaining high quality parts, enhanced material response and enhanced properties. There are many different types of FDM machines available in the market. These machines differ in size, build speed, type of material, build volume and range of process parameter settings. To understand the mechanical properties and material behavior of FDM parts, the effects of the process parameters on the quality characteristic of the parts must be studied more thoroughly. A summary of published work on optimization of FDM process parameters using DOE method to investigate the effects of various process parameters on the outputs is presented in Table 1.

Table 1 indicates that various statistical optimization methods have been widely used to study the process conditions of FDM rapid prototyping process. The applications of the Taguchi method and ANOVA procedure are found to be dominant among those optimization techniques. However, Taguchi method can only determine the best combination of levels of process variables and the interaction effects [36]. From Table 1, it is observed that the critical process parameters are identified using the ANOVA procedure. These significant input parameters are air gap, layer thickness, raster angle, raster width and build orientation. However, some published works in optimizing process parameters have not evaluated the lack-of-fit (LOF) in their experiments which perhaps indicated that the model was not fit for all the design points well. In this case, the experimental design probably needs to be extended with more runs to estimate the interactions in more accurate way.

Based on the literature review, it is clear that several optimization techniques such as RSM, Taguchi method, full factorial, gray relational, fractional factorial, ANN, fuzzy logic and GA have been used for optimizing FDM operating parameters. Table 2 shows an overview of DOE used for optimization of FDM process parameters. Taguchi method is an effective tool for optimizing FDM process parameters. Taguchi method provides simple, reliable and effective approach in practical applications to improve the product quality at low cost. It is noted that the Taguchi method can reduce the number of experiments significantly in comparison with RSM [37]. In Taguchi method, optimum parameter settings can be determined using different

Table 1 Summary of published work on FDM process optimization

References	Methods	Materials	Inputs	Outputs	Significant inputs
Anitha et al. [14]	Taguchi method, (S/N) & ANOVA procedure	ABS	Layer thickness, road width, speed of deposition	Surface roughness	Layer thickness
Thrimurthulu et al. [16]	GA	ABS	Slice thickness, build deposition orientation	Surface finish and build time	All input parameters
Nancharaiah et al. [15]	Taguchi method, ANOVA procedure	ABS	Layer thickness, road width, raster angle, air gap	Surface quality and dimensional accuracy	All input parameters
Horvath et al. [17]	2^3 and 3^2 full factorial designs	ABS	Model temperature, layer thickness, part fill style	Surface roughness	Layer thickness
Wang et al. [18]	Taguchi method, ANOVA along with gray relational analysis	ABS	Layer thickness, deposition style, support style, deposition orientation	Tensile strength, dimension accuracy and surface roughness	Layer thickness and deposition orientation
Sood et al. [19]	Gray Taguchi method, ANN	ABS	Part orientation, road width, layer thickness, air gap, raster angle	Dimensional accuracy	Build orientation
Zhang and Peng [20]	Taguchi method	ABS	Wire-width compensation, extrusion velocity, filling velocity, layer thickness	Dimensional error and warpage deformation	All input parameters
Sahu et al. [21]	Taguchi method, fuzzy logic	ABS	Layer thickness, orientation, raster angle, raster width, air gap	Dimensional accuracy	All input parameters
Lee et al. [22]	Taguchi method, ANOVA procedure	ABS	Air gap, raster angle, raster width, layer thickness	Elastic performance	Air gap, raster angle and layer thickness
Laeng et al. [23]	Taguchi method, ANOVA procedure	ABS	Air gap, raster angle, raster width, slice height	Elastic performance	Air gap, raster angle and slice height
Zhang and Chou [24]	Finite element analysis, CCD & ANOVA	ABS	Scan speed, layer thickness, road width	Residual stresses and part distortion	Scan speed, layer thickness
Nancharaiah [25]	Taguchi's design, ANOVA procedure	ABS	Layer thickness, air gap, raster angle	Production time	Layer thickness, air gap
Kumar and Regalla [26]	2^5 full factorial design, ANOVA procedure	ABS	Layer thickness, raster angle, orientation, contour width, part raster width	Support material volume, build time	All input parameters
Ahn et al. [27]	2^5 full factorial design	ABS	Air gap, raster orientation, bead width, raster width, model temperature, color	Tensile strength, compressive strength	Air gap, raster orientation
Ang et al. [28]	2^5 full factorial design	ABS	Air gap, raster width, build orientation, build laydown pattern, build layer	Porosity, compressive yield strength, compressive modulus	All input parameters
Sood et al. [29]	CCD, ANOVA procedure	ABS	Layer thickness, orientation, raster angle, raster width, air gap	Tensile, flexural and impact strength	All input parameters
Percoco et al. [30]	CCD	ABS	Raster width, raster angle, immersion time	Compressive strength	Raster width
Rayegani and Onwubolu [31]	2^4 full factorial design, GMDH & DE	ABS	Part orientation, raster angle, raster width, air gap	Tensile strength	All input parameters
Masood et al. [32]	Laboratory experiment	PC	Build styles, raster angle, raster width	Tensile strength	Not applicable
Arivazhagan et al. [33]	Laboratory experiment	PC	Build styles, raster angle, raster width	Storage modulus, complex viscosity, loss modulus and Tan δ	Not applicable
Arivazhagan and Masood [34]	Laboratory experiment	ABS	Build styles, raster angle, raster width	Storage modulus, complex viscosity, loss modulus and Tan δ	Not applicable
Jami et al. [35]	Laboratory experiment	ABS	Build orientations	High-strain-rate behavior	Not applicable

Table 2 Comparison between the common experimental designs and optimization techniques

Capability	Techniques							
	Taguchi method	GA	Fuzzy logic	Gray relational	ANN	GMDH	Factorial design	RSM
Understanding	Normal	Difficult	Difficult	Normal	Moderate	Moderate	Easy	Moderate
Multi-response optimization	No	Yes	Yes	Yes	Yes	Yes	No	Yes
Uses	Widely	Rarely	Rarely	Widely	Widely	Rarely	Widely	Widely
Shape of the experimental region	Regular or irregular	Regular or irregular	Regular or irregular	Regular or irregular	Regular or irregular	Regular or irregular	Regular only	Regular only
Computational time	Short	Very long	Very long	Short	Long	Medium	Short	Short
Prediction accuracy	Low	High	High	Normal	Very high	High	Normal	Very high
Models linear dynamics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Models non-linear dynamics	No	Yes	Yes	No	Yes	Yes	No	Yes
Developing of mathematical model	No	No	Yes	No	Yes	Yes	Yes	Yes
Data requirement for a given output	Mid	High	High	Mid	High	High	Mid	Low
Optimal solution	Straight	Straight	Through model	Straight	Through model	Through model	Straight	Through model
Ability to study interaction effects between variables	Yes	No	No	Yes	No	No	Yes	Yes
Availability in simulation software	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

signal to noise ratios, depending on the goal of experiment. However, in Taguchi method, two-factor interactions are confounded with other two factors and higher interactions, which leads to non-optimal global solution. The prediction models cannot be developed and they are not suitable in advanced manufacturing process such as FDM due to the need of multiple-response quality criteria and high quality of fitting models.

The RSM is considered to be a more promising method for optimization as it gives very low standard error towards experimental verification. The most important response surface methods used frequently are the CCD and Box-Behnken design. It can be noted that RSM is a powerful optimization design in achieving the optimal solution of the problem because this method provides the ability to deal with higher degree of fitting models and multi-objective optimization in cases that are required to optimize more than one response (as in FDM process parameters). In addition, RSM is more powerful in identifying the critical process parameters, the main effects and interaction effects of parameters which provide enough information for experimental studies [38]. Furthermore, significance of interactions and square terms of variablers are more clearly predicted in RSM. However, in the case of problems with large number of process parameters, the experiments may be time-consuming in comparison with Taguchi design, as shown in Table 2.

Full factorial design is another method which allows the investigator to study the influences of process parameters on the response outputs. The main effects and all higher-order interactions for process parameters can be estimated. The main limitation with a full factorial design is that more experimental runs are required to achieve better precision and reduce percentage of error [38, 39]. Therefore, for most of the experiments, particularly in advanced manufacturing process such as FDM, it is time-consuming and expensive. For these reasons, researchers prefer to use fractional factorial design than full factorial design, as it requires less number of runs. But the main disadvantage of having a minimum number of experimental runs is that two-factor interactions will be confounded with interactions among three or even more factor interactions, which cannot be distinguished from each other. Thus, optimum process settings cannot be determined accurately.

In regard to the gray relational analysis, the researchers often use this method for measuring the relationship between process variables. However, from the literature review, it can be noted that in practical situation, determination of an optimal set of process variables could be very slow and the interactions between some effects may confound with other factors.

The literature review presented in previous section indicated that the empirical optimization techniques were used for optimizing process parameters of FDM rapid prototyping. ANN is the most popular empirical modelling applied to express the mathematical relationship between the process parameters and quality characteristics. It was used in the case when the relationship between input parameters and output was unknown. It has the ability to identify complex non-linear relationships between process parameters and output [40, 41]. This empirical technique however cannot be retrained in the case of adding data to an existing network. Furthermore, ANN does not provide enough information about factors and their effects on the output response if further analyses using screen experimental designs such as Plackett-Burman or full factorial ones have not been done. GA is another method of the empirical modeling used to optimize the process variables. GA is used to solve problems with multiple objectives and it is very easy to understand by the rapid prototyping practitioners without need of deep mathematics knowledge [42]. Through GA, however, variant problems cannot be solved due to poor fitness functions. It is noted that the main advantage of fuzzy logic is that it does not require training data compared to ANN. However, fuzzy logic approach requires developing rule and database. Thus, rapid prototyping practitioners must have in-depth knowledge of mathematics. Moreover, fuzzy logic requires a large amount of data storage, which may slow down the process.

5 Research gap, problem and challenge

As mentioned earlier, different process parameters have effects on the part quality of FDM. Essentially, the quality characteristics of FDM build part such as flexural strength, hardness, tensile strength, compressive strength, dimensional accuracy, surface roughness, production time, yield strength and ductility are the primary concerns to the manufacturers and users. Recent years, research has been targeting into identifying the optimal process parameters to improve surface finish, aesthetics, mechanical properties, model material consumption and build time. However, there are still no perfect optimal conditions for all types of parts and materials. For most parts, there is always a need to adjust parameters to balance a tradeoff between production time, surface finish, and dimensional accuracy. The properties of the FDM fabricated parts can be controlled by the selected build styles and other FDM parameters. FDM processed parts normally have lower mechanical properties and surface finish than the parts made by conventional manufacturing process such as injection moulding. To improve the part quality and mechanical properties for FDM fabricated parts, it is necessary to understand the relationship between material properties and process parameters. Thus, new mathematical modeling approaches and optimization techniques need to be developed. After reviewing past research works relevant to the areas conducted by the researchers, where main focus was on the optimization of process variables for FDM, the research work leaves a wide scope of improvements and hence more future researches can be performed to explore many aspects of FDM. The following observations are made for future research.

The literature review indicates that much research work has been attempted to improve the mechanical properties and part quality for FDM fabricated ABS parts by optimizing one or several important process parameters. From previous studies, it has been shown that the quality of FDM built part is highly affected by various process variables. Hence, the identification of the critical process parameters and determination of optimum process parameters can lead to the quality improvement of FDM fabricated part. However, the relationships between the process parameters and the part quality and mechanical properties have not been studied enough especially for various types of materials used by the FDM process. It remains a matter of concern that there are no absolute rules and guidelines designed to assist in their optimization and evaluation method. The FDM liquefier head is designed to be capable of dealing with different kinds of materials such as ABS, polyphenylsulfone (PPSF), PC-ABS, PC, PC-ISO, nylon-12, elastomer and wax. Amongst them, PC, PC-ISO, PC-ABS and PPSF are widely used for FDM process and their applications are growing rapidly in the global market of manufacturing. Many studies have investigated the effects of FDM process parameters on ABS built part. However, in case of other FDM materials, very little work has been done both in terms of material characterization and FDM process optimization. Therefore, considerable work remains to be done in DOEs for part fabrication and process optimization involving other FDM polymers such as PC, PPSF, PC-ABS, PC-ISO, elastomer and nylon-12.

In terms of material properties, most of the studies are mainly focused on optimizing the process parameters for mechanical properties of ABS parts. However, there have been no published research articles relating to the optimization of FDM process variables for thermal, chemical and dynamic mechanical properties of FDM fabricated parts in other material forms. Therefore, much research work is needed in this area in the future research.

Effects of process parameters on surface roughness, tensile strength, compressive strength, flexural, impact strength and dimensional accuracy have been studied. But the study needs to be extended to other types of quality characteristics such as hardness, production time, creep, vibration, product and process cost, porosity and stress strain behavior at high-strain-rate loading conditions. Future work should also focus on the application of new statistical designs, modeling and optimization techniques to find out the optimal combinations for a certain set of process parameters and test the functionality of FDM processed part in an efficient manner.

Environmental factors such as temperature and relative humidity are also considered to be the sources of error affecting part accuracy. FDM materials such as ABS, PC, nylon-12 and PC-ABS blend may be affected by these factors, and they may have an effect on dimensional accuracy as well as surface finish. Therefore, determining the optimum values of temperature and humidity may need to be studied in various forms of materials.

There are some physical constraints imposed on FDM machine, which affect the selection of the optimal process settings and must be taken into consideration in the future research. The first constraint is that some FDM machines allow only four specific values of layer thickness which are 0.1270, 0.1778, 0.2540 and 0.3302 mm. Apart from these, the operator can not select any other value because they are restricted by the nozzle diameter. The second practical constraint is that each nozzle diameter has its own raster width range. The third practical constraint is that when the operator needs to use different number of contours, these are limited to the specific values. In this case, the operator will not be able to use any other values between this range. Therefore, optimization of FDM process parameters is complicated when many such constraints are also included. So, it will be difficult for the traditional DOEs to solve such kind of problem. Thus, developing new optimization approaches and mathematical modeling is needed to solve such type of constraints in order for the optimal parameters to be feasible and possible in practical applications.

6 Conclusions

This article presents a review of research work carried out in the determination and optimization of the process parameters for FDM. This article also outlines the directions for future FDM research. A number of research works based on various optimization techniques were reviewed including RSM, Taguchi method, full factorial, gray relational, fractional factorial, ANN, fuzzy logic and GA. A review of research work on various optimization techniques indicated that there were successful industrial applications of Taguchi method, RSM, GA and ANN. These are robust optimization techniques to make experimental design insensitive to uncontrollable factors such as environmental parameters to predict responses and optimize the FDM process conditions in accuracy level. The paper has also identified several critical areas of future research in optimizing and characterizing the FDM process and FDM materials. It has emphasized that FDM is characterized by a large number of process variables that determine the mechanical properties and quality of fabricated parts. Much research work has been attempted to improve the mechanical properties and part quality for FDM fabricated ABS parts through statistical design optimization. However, modeling and optimization of FDM process with other leading FDM materials such as PC, PC-ABS, PPSF, etc., have not been undertaken. Furthermore, characterization and optimization of FDM process parameters in terms of other properties through new statistical experiment design and optimization techniques are also nonexistent in the literature. These future works will provide a wealth of knowledge in making the FDM process an ideal additive manufacturing process for engineering applications with high part quality, accuracy and desired properties. Overall literature review shows that process parameters including air gap, layer thickness, raster angle, raster width and build orientations are the critical factors and these must be studied and analyzed in future research.

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