

Optimization of Process Parameters in Fused Deposition Modeling: A Review

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ABSTRACT: Fused Deposition Modeling (FDM) is one of the most popular additive manufacturing technologies for various engineering applications. Stratasys Inc., USA, has introduced FDM process commercially in early 1990s. 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. This study includes identification of various process parameters involving in FDM, which affects part quality. This study aims to find effects of process parameters on different performance parameters based on previous research done. This study also aims to compare different optimization techniques and identify the suitable technique for performing optimization of process parameters in Fused Deposition Modeling.

KEYWORDS: Fused Deposition Modeling (FDM), Rapid Prototyping (RP), Additive manufacturing, Process parameters, Performance parameters, Mechanical properties, Part quality.

I. INTRODUCTION

Fused Deposition Modeling (FDM) is a fast growing Rapid Prototyping (RP) technology due to its ability to build functional parts having complex geometrical shapes in reasonable build time. Reduction of product development cycle time is a major concern in industries to remain competitive in the marketplace, and hence, focus has shifted from traditional product development methodology to rapid fabrication techniques such as RP. Although RP is an efficient technology, full-scale application has not gained much attention because of compatibility of presently available materials with RP technologies. To overcome this limitation, one approach may be the development of new materials having superior characteristics than conventional materials and its compatibility with technology. Another convenient approach may be suitably adjusting the process parameters during fabrication stage so that properties may improve. A critical review of literature suggests that properties of RP parts are the function of various process related parameters and can be significantly improved with proper adjustment. Since mechanical properties are important for functional parts, it is absolutely essential to study the influence of various process parameters on mechanical properties so that improvement can be made through selection of the best settings. FDM is one of the RP processes that build part of any geometry by sequential deposition of material on a layer by layer basis. The process uses heated thermoplastic filaments which are extruded from the tip of the nozzle in a prescribed manner in semi molten state and solidify at chamber temperature. The properties of built parts depend on the settings of various process parameters fixed at the time of fabrication. Fig. 1 shows the principle of FDM process.

Producing aesthetically appealing additive manufacturing products that have complex shapes is not difficult. The challenge is to produce additive manufactured parts that are functionally reliable. This paper presents a comprehensive review of FDM process parameter optimization involving 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.

II. 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. Several statistical optimization techniques have been

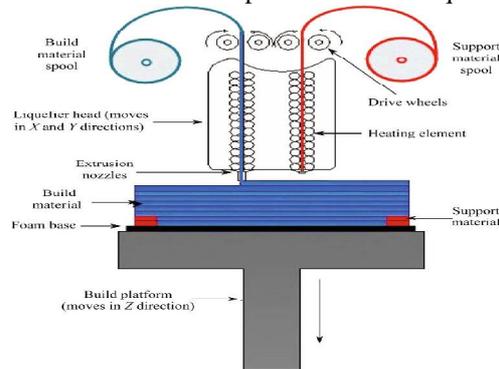
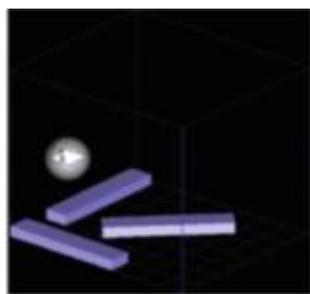


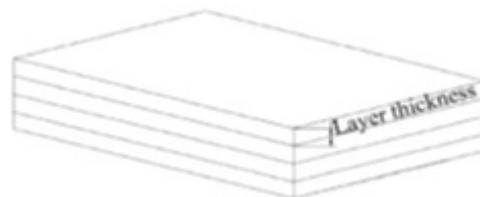
Fig. 1 Principle of FDM process

successfully used for the optimization of process conditions of FDM rapid prototyping technology. Figure 2 shows the meanings of some FDM process parameters. Some main parameters are also described as follows.

1. 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. 2a.
2. Layer thickness is the thickness of layer deposited by nozzle tip, as shown in Fig. 2b. The value of layer thickness depends on the material and tip size.
3. Air gap refers to the gap between adjacent raster tool paths on the same layer, as shown in Fig. 2c.
4. 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°.



(a)



(b)

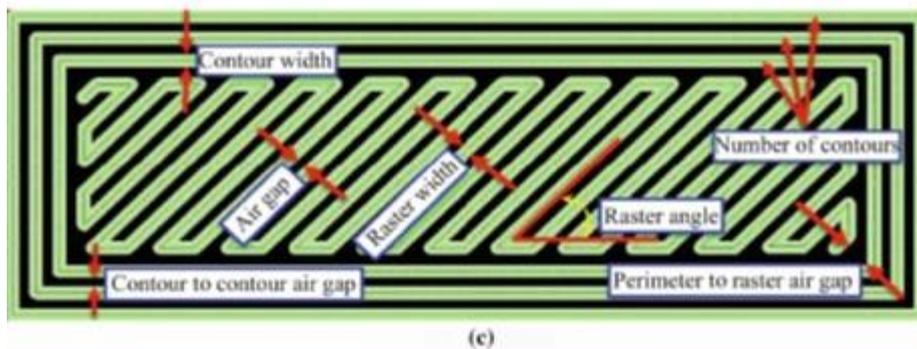


Fig. 2 (a) Build orientations, (b) layer thickness, and (c) FDM tool path parameters

5. 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.
6. Contour width refers to the width of the contour tool path that surrounds the part curves.
7. The number of contours to build around all outer and inner part curves is shown in Fig. 2c. Additional contours may improve perimeter part walls.
8. Contour to contour air gap refers to the gap between contours when the part fill style is set to multiple contours.
9. Perimeter to raster air gap refers to gap between the inner most contour and the edge of the raster fill inside of the contour.

III. PERFORMANCE PARAMETERS

Performance parameters are those for which the optimization is going to perform. Optimization of process parameters needs at least one performance parameter. For example, optimization of FDM process parameters for maximum tensile strength of fabricated part, so here Tensile strength is the performance parameter. Some performance parameters that are going to study in this paper are as follows.

1. Built Time

Fabrication of part using FDM is quite time consuming process so there must be need to minimize the total time required to complete part fabricated using FDM.

2. Flexural Strength

For getting functioning part fabricated from FDM, part must possess good strength. Strength must be either tensile, compressive or shear depends upon the application.

3. Surface Roughness

For getting functioning part fabricated from FDM, part must possess good surface roughness depend upon the application where that part is going to perform.

4. Feed Stock Material Consumption

Materials used in FDM are quite costlier. So the basic aim is to fabricate part using FDM with less cost, that can be achieve by minimizing material used for fabrication of the part.

5. Dimensional Accuracy

This can also consider as performance parameter in optimization of FDM process parameters as dimensional accuracy is very important factor where mating of two part are fabricated using FDM.

IV. RESEARCH ON FDM PROCESS PARAMETERS

FDM process conditions play an important role in improving surface roughness, dimensional accuracy, mechanical properties, material behaviour 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 sections, research on each performance parameters is reviewed in detail.

1. Effect on Built time

From previous studies, it is found that build orientation, layer thickness and air gap are the significant process variables that affected the build time. It was also reported that the layer thickness and air gap contributed 66.57% and 30.77% respectively on the build time.

2. Effect on Flexural Strength

Layer thickness and Air gap mainly affects the strength of the part. Increasing layer thickness increases the tensile strength. And negative air gap tends to the high value of strength. Part orientation is also somehow affects strength; tensile strength is more in the direction of orientation.

3. Surface Roughness

The study revealed that the factor having the most important influence on the surface roughness was the layer thickness and road width. Surface roughness could be improved by using lower value of layer thickness and air gap because it reduced the voids between layers.

V. RESEARCH ON OPTIMIZATION TECHNIQUES

There are various optimization methods have been widely used to study the process conditions of FDM rapid prototyping process. Applications of the Taguchi method and ANOVA procedure are found to be dominant among those optimization techniques.

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. However, Taguchi method can only determine the best combination of levels of process variables and the interaction effects.

The RSM is considered to be a more promising method for optimization as it gives very low standard error towards experimental verification. 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. 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, more number of run is required to get accurate output. Based on the literature review, it is clear that several optimization techniques such as RSM, Taguchi method, full factorial, fuzzy logic and GA have been used for optimizing FDM operating parameters. It is noted that the Taguchi method can reduce the number of experiments significantly in comparison with RSM.

Table 1. Summary of published work on FDM process optimization

References	Methods	Materials	Inputs	Outputs	Significant Inputs
Omar Ahmed Mohamed (2016)	Response Surface Methodology Analysis of variance (ANOVA)	ABS	Part Orientation, Road Width, Layer Thickness, Air Gap, Raster Angle, No. Of Contours	Dynamic Flexural Modulus	Layer Thickness, Air Gap, Build Direction And No. Of Contours
Jianlei Wang	Experimental	ABS	Heating Temperature	Mechanical	All Input

(2016)			And Heating Time	Properties	Parameters
C.A. Griffiths (2016)	Experimental	Polylactic Acid	Slice Orientation	Energy Consumption, Part Weight	Slice Orientation
Omar Ahmed Mohamed (2015)	I-optimality criterion, Analysis of variance (ANOVA)	ABS	Part Orientation, Road Width, Layer Thickness, Air Gap, Raster Angle, No. Of Contours	Dimensional Accuracy	Layer Thickness, Air Gap, Build Orientation, Road Width, And No. Of Contours
Mahdi Kaveh (2015)	Experimental	ABS, HIPS	Temperature, Feed Rate, Raster Width	Dimensional Accuracy And Internal Cavity	All Input Parameters
R. Venkata Rao (2015)	Teaching learning based optimization algorithm	ABS	Line Width Compensation, Filling Velocity, Layer Thickness	Mechanical Properties	All Input Parameters
Rayegani and Onwubolu (2014)	2 ⁴ full factorial design, GMDH & DE	ABS	Part Orientation, Raster Angle, Raster Width, Air Gap	Tensile Strength	All Input Parameters
Tejendrasinh S. Raol (2014)	Response Surface Methodology	ABS	Part Orientation, Layer Thickness, Raster Angle	Surface Roughness	Part Orientation, Layer Thickness
Zhang and Peng (2012)	Taguchi method	ABS	Wire Width Compensation, Extrusion Velocity, Filling Velocity, Layer Thickness	Dimensional Error And Warpage Deformation	All Input Parameters
A.K. Sood (2010)	Gray Taguchi method,	ABS	Part Orientation, Road Width, Layer Thickness, Air Gap, Raster Angle	Dimensional Accuracy	Build Orientation
Nancharaiah (2010)	Taguchi method, ANOVA procedure	ABS	Layer Thickness, Road Width, Raster Angle, Air Gap	Surface Quality And Dimensional Accuracy	All Input Parameters
D. Horvath (2007)	2 ³ and 3 ² full factorial designs	ABS	Model Temperature, Layer Thickness, Part Fill Style	Surface Roughness	Layer Thickness

VI. RESEARCH GAP

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 literature review indicates that much research work has been attempted to improve the mechanical properties and part quality for FDM fabricated ABS parts. 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. The FDM liquefier head is designed to be capable of dealing with different kinds of materials such as ABS, PC-ABS, PC, nylon-12, elastomer and wax. Amongst them, PC, PC-ISO and PC-ABS 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 part fabrication and process optimization involving other FDM polymers such as PC, PC-ABS, 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.

VII. CONCLUSION

This paper presents a review of research work carried out 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 and Taguchi method. A review of research work on various optimization techniques indicated that there were successful applications of Taguchi method and RSM. 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 critical areas of future research in optimizing and characterizing the FDM process and FDM materials. 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, etc., have not been undertaken. 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.

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