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Analysis of Process Parameters of Fused Deposition Modeling (FDM) Technique

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Abstract:- Fused deposition modeling (FDM) is one of the RP technique in which a plastic filament is melted in the extruder of the 3D printer and deposited on the build platform of the 3D printer to form the object layer by layer. Part quality and mechanical properties of the FDM fabricated parts extensively depends on process variable parameters such as layer thickness, raster angle, part orientation, raster width, air gap. Hence, selection and optimization of FDM process parameters is vital. The aim and objective of this article is to study and determine the influence of these parameters on processed part through the research work carried out so far. A number of optimization techniques and designs of experiments for the determination of optimum process parameter have been studied.

Keywords*: Fused deposition modeling (FDM), ABS, rapid prototyping (RP), process parameters, mechanical properties.*

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Introduction:

The competition between manufacturing industries has incremented enormously in recent years. Now it has turned out to be vital that the new merchandise to hit the market as early as possible for attaining competitive advantage. Focus of industries has shifted from conventional product development methodology to rapid manufacturing techniques like rapid prototyping (RP) technique to shorten the product development cycle time. Part of any complex geometry can be made in least possible time by RP technique due to absence of tooling. Rapid prototyping is an additive manufacturing (AM) technique in which the final object is produced from CAD model by successively depositing material in layers. Although RP technology has proven its effectiveness in industries, there is a limitation that some presently available materials are not compatible with RP technologies. This limitation can be overcome by either development of new materials or adjusting the process parameters during fabrication stage to get better mechanical properties. Hence it is indispensable to optimize the operation parameters to enhance the accuracy, quality and properties of the part produced from RP technique. FDM is one of the RP techniques [1] in which strands of heated thermoplastic are extruded from a nozzle that travels in the two dimensional plane. The controlled extrusion head deposits very thin beads of material in semi molten state onto the build platform to form the first level. After the platform lowers, the extrusion head place a second layer upon the first. Supports are fabricated along the path; tie up to the part either with a second weaker material or with a perforated junction. Figure 1 shows the principle of FDM process.

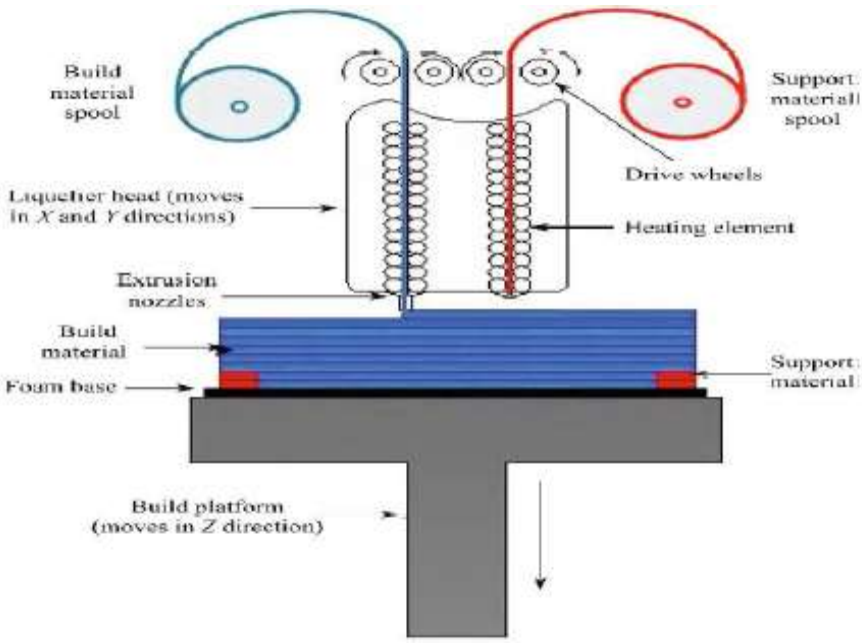

Figure 1: Principle of FDM process [15]

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The accuracy, quality and properties of additive manufactured part greatly depend upon the process parameters. Therefore, any attempt to develop functionally reliable part from FDM process should also necessarily involve the fundamental studies of various process parameters. This paper reviews the effect of FDM process parameters and optimization of process parameters involving optimization techniques. Some important parameters of FDM are illustrated below and are explained with the help of figures 2 and 3:

1. **Build orientation** is the angle which a part makes with the build platform with respect to x, y and z axes.
2. **Layer thickness** is the thickness of the layer placed by nozzle tip, as shown in Figure 3b. The amount of layer thickness depends on the nozzle diameter and material.
3. **Air gap** is the distance between two contiguous raster tool conduits on the same layer, as shown in Figure 3c.
4. **Raster angle** refers to the angle made by the raster model with respect to the X-axis on the underside part layer. The typical permitted raster angles are from 0º to 90º.
5. **Raster width** is the breadth of the material bead used for rasters. The larger value of the raster width will build a component with a more vigorous interior. The amount of raster width depends on nozzle tip diameter.
6. **Contour width** refers to the width of the contour tool path that encloses the component coils.
7. **Contour to contour air gap** refers to the distance between contours when the component packing style is set to several contours.

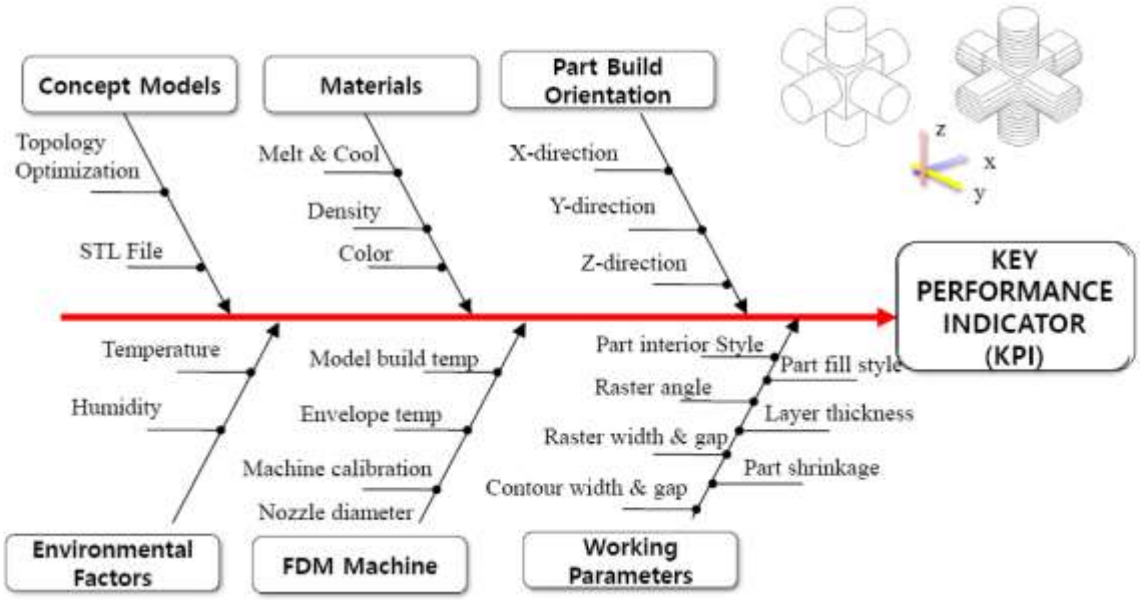
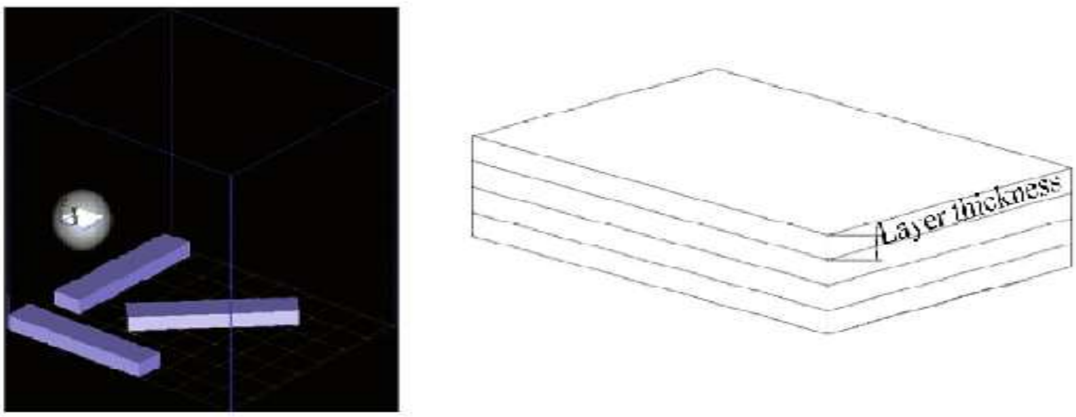


Figure 2: Cause and effect diagram of FDM process parameters [16]



(a) (b)

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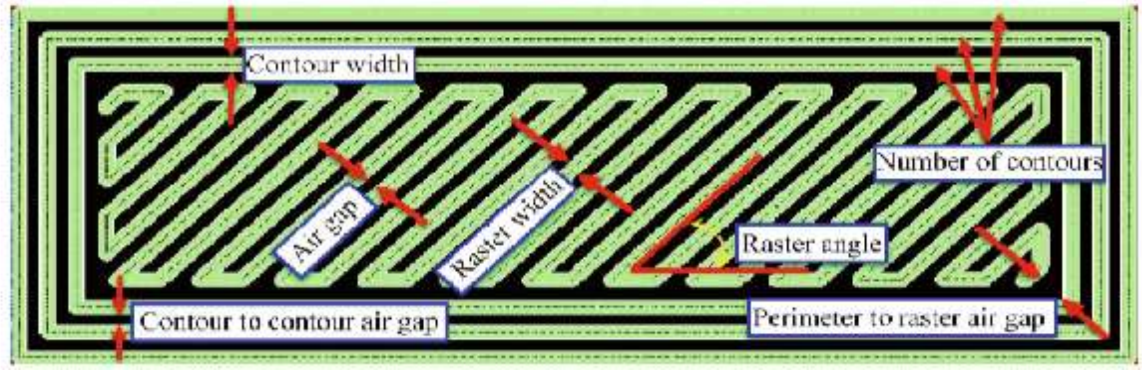

(c)

Figure 3(a) Part orientation **(b)** Layer Thickness **(c)** Parameters of tool path [16]

Literature Survey:

In view of the inherent advantages of employing RP technique in fabrication of a part, FDM is one of the RP processes is extensively used. Dimensional accuracy, quality and mechanical properties of a part material are dependent on process parameters. Hence, study of these parameters is of paramount importance. Appropriate optimization techniques are suggested by many researchers to study the effects of process parameters on different processed parts. Under this section, the extensive literature survey conducted on this aspect is presented.

Jason Cantrell et al. [2] studied the directional properties of the material made from acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) by selecting the four raster angles ([0/90], [+15/-75], [+30/-60] and [+45/-45]) and three build orientations (up-right, flat and on-edge) and found the following observations in his investigations:

- Young's modulus and Poisson's ratio of ABS specimens were found isotropic in nature.
- Strain energy density, strain at failure and ultimate strength of ABS specimens were found anisotropic. Strain energy density for [+45/-45] flat orientation was found 91% higher than that of [+45/-45] up-right orientation.
- Tensile and shear properties of ABS specimens were unaffected by raster orientation.
- In the on-edge orientation the PC specimens appeared nearly isotropic while in the flat and upright printer orientations they revealed a huge amount of anisotropy.
- Tensile properties were highest for the on-edge PC specimen and shear strengths were highest for the [+45/-45] flat orientation specimens.

Overall a large amount of anisotropy was found in specimens when raster and build orientation were varied which should be consider while producing a part by 3D printing.

Miguel Fernandez-Vicente et al. [3] studied the effect of pattern and infill density on tensile mechanical behavior in desktop 3D printing. In this study three levels of infill parameter were evaluated: 20%, 50% and 100% and three most widely used patterns were evaluated: line, rectilinear and honeycomb. The results of their investigation indicate that maximum tensile strength was obtained when pattern was rectilinear with infill density of 100%.

P.J. Nuñez et al. [4] studied the quality parameters viz. dimensional accuracy, flatness error, and surface texture in manufactured products obtained from FDM with ABS-plus as the model material. For the analysis of surface texture and flatness they designed work pieces of dimensions 20 mm*20 mm*10 mm, two layer thicknesses of 0.178 mm and 0.254 mm and three densities of 10%, 50% and 100%. From their experimental study they found the following results as shown in table 1.

Table 1: Results from experimental study of P.J. Nuñez et al.

S. No.	Findings	Layer thickness (mm)	Density (%)
1	More dimensional accuracy	0.254	100
2	Better surface finish	0.178	100
3	Minimum flatness error	0.178	100

Anoop Kumar Sood et al. [5] considered five important process parameters viz. layer thickness, raster width, raster angle, air gap and part orientation along with their interaction on dimensional accuracy of fused deposition modeling (FDM) process ABS parts. Grey Taguchi method was used to optimize percentage change in length, width and thickness and found the following results as shown in table 2.

Table 2: Values of process parameters to minimize percentage change in part dimension

S. No.	Part dimension	Layer thickness (mm)	Part Orientation (degree)	Raster angle (degree)	Raster width (mm)	Air gap (mm)
1	Length	0.254	0	60	0.4564	0.008
2	Width	0.254	0	30	0.4564	0.004
3	Thickness	0.127	0	0	0.5064	0.004

Overall improvement in part dimension was found for layer thickness of 0.178 mm, part orientation of 0^0, raster angle of 0^0, road width of 0.4564 mm and air gap of 0.008 mm.

Omar Ahmed Mohamed et al. [6] established the relationship between FDM process conditions and time dependent mechanical property like creep displacement by using definitive screening design with PC-ABS as the model material. A total of 13 PC-ABS specimens having dimensions 60 mm*12.5 mm*3.5 mm were fabricated. This study revealed that creep displacement varies directly with the layer thickness, raster angle and air gap and inversely with the raster width and number of layers. The raster width of 0.4572 mm, part orientation of 20°, layer thickness of 0.2540 mm, raster angle of 0°, air gap of 0 mm and 8 shells were found to be the optimum conditions.

Anoop Kumar Sood et al. [7] studied the effect of five FDM process parameters viz. slice thickness, raster width, raster angle, gap between two layers and part orientation on three mechanical properties viz. tensile, flexural and impact strength of ABS test specimen. A number of response surfaces were drawn which shows the following results (table 3):

Table 3: Effect of process parameters on mechanical properties

Change in Parameter	**Effect on tensile strength**
Increment in layer thickness	First decreases, then increases
Increase in Raster width	Increases
Increase in Raster angle	Increases
Positive air gap	Increases
Increase in part orientation	Decreases

Change in Parameter	**Effect on flexural strength**
Increment in layer thickness	Decreases
Increment in Raster width	Raises
Increment in Raster angle	Increases then decreases at higher values
Positive air gap	Increases
Increase in part orientation	Decreases

Change in Parameter	**Effect on impact strength**
Increment in layer thickness	not defined
Increment in Raster width	increases then decreases
Increment in Raster angle	not defined
Positive air gap	not defined
Increase in part orientation	increases then decreases

S. Dinesh Kumar et al. [8] experimentally investigated the effect of FDM process parameters on surface roughness of the *ABS-M30i* parts produced by FDM. Parameters taken in these experiments were slice height, raster width, raster angle, contour width and gap between two layers. A design of experiments was made having two levels for each process parameter to conduct experiments by using Taguchi method as shown in table 4.

Table 4: Design of experiments

Variable parameter	**Low level**	**High level**
Slice height	0.254 mm	0.353 mm
Air gap	0 mm	-0.01 mm
Raster width	0.508 mm	0.8 mm
Contour width	0.508 mm	0.8 mm
Raster angle	$45^0/-45^0$	$45^0/90^0$

They concluded that the surface roughness can be reduced by using slice height at 0.254 mm, negative air gap at -0.01 mm and raster width at 0.508 mm. They also found that to reduce the requirement of support material optimization of part orientation is vital which would further improve the surface finish and reduce the build time.

R. Anitha et al. [9] used Taguchi's design matrix, signal to noise ratio (S/N) and analysis of variance (ANOVA) to investigate the effect of three process parameters viz. layer thickness, speed of deposition and road width on surface roughness of ABS prototype. They found that the surface roughness was greatly influenced by layer thickness and it was also studied that the surface roughness decreases with increase in layer thickness.

K. Thrimurthulu et al. [10] optimized the part deposition orientation for FDM process for reducing build time and enhancing part surface finish. They used a real coded genetic algorithm to obtain the optimum solution. This study concluded that the optimum build orientation for any intricate freeform surfaces could be predicted by the developed model with the limitation that it cannot be used to predict other process parameters.

T. Nancharaiah et al. [11] applied Taguchi method to study the effect of the process parameters road width, air gap, layer thickness and raster angle on the surface finish and dimensional accuracy. From the design of experiments and ANOVA analysis it was found that properties (i.e. dimensional accuracy and surface finish) did not show any clear indication of its dependence on raster angle but variation of air gap, layer thickness and road width were seen to have a considerable effects on dimensional accuracy and insignificant effect on surface quality. Following important rules revealed from this research work:

- At lower value of layer thickness better surface finish and dimensional accuracy could be obtained.
- Surface quality could be improved by using large bead width and dimensional accuracy could be improved by moderate bead width.
- Surface quality and dimensional tolerances degrade from negative air gap.

Zhang Jinwen et al. [12] applied Taguchi method with fuzzy logic to control the dimensional error and warpage deformation by optimizing the four process parameters viz. raster width compensation, layer thickness, infill velocity and feed velocity. The part material used in this study was ABS engineering plastics having dimensions 60mm*20 mm*9mm. The study concluded that the most significant influencing factor was raster width compensation followed by feed velocity, layer thickness and infill velocity. They reported the following optimum combinations of process parameter for dimensional error and warpage deformation (table 5)

Table 5: Value of optimized parameters for dimensional error and warpage deformation

S. No.	Output	Input			
		Raster width compensation (mm)	Feed velocity (mm/sec)	Infill velocity (mm/sec)	Layer thickness (mm)
1	Dimensional error	0.17	20	30	0.15
2	Warpage deformation	0.17	25	20	0.3

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B.H. Lee et al. [13] investigated four important process parameters viz. air gap, raster angle, raster width and layer thickness in order to optimize elastic performance of a compliant ABS prototype by employing Taguchi method and Anova procedure. The results concluded that elastic property of the work material was greatly influenced by air gap, layer thickness and raster angle.

Gianluca Percoco et al. [14] analyzed the effect of chemical treatment and immersion time on mechanical properties of FDM produced part. The results was concluded that compressive strength of chemically treated part is better than untreated one due to the alteration of surface roughness up to 90%. It also concluded that the optimized immersion time for chemical treatment was up to 300 seconds.

O. S. Es-Said [15] et al. studied the effect of layer orientation on mechanical properties viz. tensile strength, flexural strength and impact strength of rapid prototyped samples obtained from FDM with ABS as model material. In this study parts were processed at 0^0, $45^0/-45^0$, 45^0, 90^0 and 45^0 orientations. This study concluded that ultimate and yield strengths were the highest in the 0° orientation followed by the 45/0°, 45/-45°, 90° orientations in descending order, Flexural strength was highest in the 0° orientation followed by equivalent values in the 45/-45°, 90° orientations in descending order, impact strength was highest in the 0° orientation by an order of magnitude over the 90° orientation. The impact strength values of other orientations were equivalent (45/0° = 45° = ± 45°).

Following table showing the various process parameters studied in this article:

S.No.	References	Material	Inputs	Outputs	Method
1	Jason Cantrell et al. [2]	ABS and PC	raster angle and build orientation	Young’s modulus and Poisson’s ratio, Tensile and shear properties	Experimental study
2	Miguel Fernandez-Vicente et al. [3]	ABS	pattern and infill density	tensile strength	ANOVA procedure
3	PJ Nunez et al. [4]	ABS plus	layer thickness, density	dimensional accuracy, flatness error and surface finish	Experimental study
4	Anoop Kumar Sood et al. [5]	ABS	layer thickness, orientation, air gap, raster angle, raster width	dimensional accuracy	Grey Taguchi method
5	Anoop Kumar Sood [7]	ABS	layer thickness, orientation, air gap, raster angle, raster width	tensile, flexural, impact strength	ANOVA and Central composite design (CCD)
6	Omar Ahmed Mohamed et al. [6]	Polycarbonate-ABS	layer thickness, air gap, part orientation, raster width, raster angle	creep displacement	Quadratic model
7	S.Dinesh Kumar et al. [8]	*ABS- M30i*	layer thickness, contour width, air gap, raster orientation, raster width	surface roughness	Taguchi method and Anova procedure
8	R. Anitha et al. [9]	ABS	layer thickness, speed of deposition and road width	surface roughness	Taguchi, (S/N) and Anova procedure
9	K. Thrimurthulu et al. [10]	ABS	slice thickness, build deposition orientation	surface finish and build time	GA
10	T. Nancharaiahet al. [11]	ABS	layer thickness, road width, raster angle and air gap	surface finish and dimensional accuracy	Taguchi method and Anova procedure
11	Zhang Jinwen et al. [12]	ABS	Filling velocity, extrusion velocity, Wire-width	Dimensional error and	Taguchi method

			compensation, layer thickness	warpage deformation	
12	B.H. Lee et al. [13]	ABS	Air gap, raster angle, raster width, layer thickness	Elastic performance	Taguchi method and Anova procedure
13	Gianluca Percoco et al. [14]	ABS	Raster width, raster angle, immersion time	Compressive strenth	CCD
14	O. S. Es-Said et al. [15]	ABS	Part orientation	Ultimate and yield strength, flexural strength, impact strength	tensile test, three point bending test, Izod test

Conclusion:

In this article, the effects of FDM process parameters on quality, build time and mechanical properties of processed part have been studied. The results in the FDM process showed that:

- Lower value of layer thickness could be used in order to obtain a more dimensionally accurate and higher surface quality part. Mechanical properties like tensile strength and flexural strength show an inverse relationship with layer thickness up to some extent and afterwards they varies directly and there is also a significant influence of layer thickness on elastic property of FDM specimen.
- Compressive strength of chemically treated part is better than untreated one.
- A positive gap between two layers indicates a clear trend with respect to tensile strength, flexural strength and creep displacement.
- Creep displacement of FDM produced parts shows inverse relationship with respect to number of layers.
- Surface finish of parts does not show clear indication of its dependence on raster width and the variation of impact strength with raster width is also seems to be random. Other mechanical properties like tensile strength and flexural strength varies directly with raster width.
- Maximum tensile strength could be obtained for rectilinear pattern with 100% infill density.
- A change in build orientation and raster angle do not affect the surface finish of the FDM produced part but build time can be reduced by optimizing build orientation.

Scope for future work:

There are some other parameters like humidity, model build temperature, part shrinkage and temperature of surrounding which are not included in presented work. The effect of these parameters can also be studied for improvement in mechanical properties and quality of the FDM produced part.

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