A PARAMETRIC STUDY OF FUSED DEPOSITION MODELING PROCESS.

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Abstract: Fused depositions modeling refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. In contrast to classical methods of manufacturing such as milling and forging which are based on subtractive and formative principles respectively, fused deposition modeling (FDM) processes are based on additive principle for part fabrication. The biggest advantage of this processes is that an entire 3D (three-dimensional) consolidated assembly can be fabricated in a single setup without any tooling or human intervention; further, the part fabrication methodology is independent of the complexity of the part geometry. FDM has significant advantages in terms of elimination of expensive tooling and flexibility. The major limitation of this process is that performance of prototypes is sensitive to process parameter variation.

Index Terms- **Additive manufacturing, fused deposition modeling, 3-D, prototype, flexibility.**

1. Introduction:

Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material (from the International Committee F42 for Additive Manufacturing Technologies, ASTM). The first techniques for AM became available in the late 1980s and were used to produce models and prototype parts. Today, they are used for a much wider range of applications and are even used to manufacture production-quality parts in relatively small numbers. The use of additive manufacturing takes virtual designs from computer aided design (CAD), transforms them into thin, virtual, horizontal cross-sections and then creates successive layers until the model is complete. The primary advantage to additive fabrication is its ability to create almost any shape or geometric feature. With the last advances, it is now possible to build physical models quicker and with more complex geometries, pushing this type of techniques from printing mockups and prototypes models towards printing final products in limited series. The different available AM techniques are Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM) and fused deposition modeling (FDM). Currently, FDM is the technique showing the higher potential for product manufacturing, with the capability to compete with conventional polymer processing techniques. Though, the range of filaments commercially available for FDM is still somehow limited and costly, which hinders the use of this technology for manufacturing final products. Neither the materials nor the process have been studied in a systematic manner towards functional components production, with adjusted mechanical properties, or with the objective of getting competitive production time/cost (for small/medium production series), respectively. The range of applications where this technique can be used is extensive, ranging from medical applications to automotive and aeronautics [1-4, 6, 7, 10, 34].

2. Fused Deposition Modeling:

Fused deposition modeling, which is often referred to by its initials FDM, is a type of additive fabrication or (sometimes called rapid prototyping/rapid manufacturing (RP or RM)) technology commonly used within engineering design. The process was developed by S. Scott Crump in the late 1980s and was commercialized in 1990. The FDM technology is marketed commercially by Stratasys, USA which also holds a trademark on the term [2, 5-10, 33].

But unlike other AM systems which involve an collection of lasers, powders, resins, this process use heated thermoplastic filaments which be extruded from the tip of nozzle in a temperature controlled surroundings. For this there is a material deposition subsystem known as head which consist of two liquefier tips. One tip intended for model material and other tip intended for support material deposition both of which works alternatively. The piece forming material is supplied to the head in the form of a flexible strand of solid material from a supply source. One pair of pulleys or rollers have a nip in flanked by are utilize as material advance mechanism to grip a flexible filament of modeling material and advance it into a heated dispensing or liquefier head. The material is heated above its solidification heat by a heater on the dispensing head and extruded in a semi molten state on a previously deposited material onto the build stage following the designed tool path. The head is attached to the coaches that move along the X-Y plane. The build platform moves along the Z direction. The drive motion are provide to selectively move the build platform and dispensing head relative to each other in a predetermined pattern through constrain signals process to the drive motors from CAD/CAM system. Once the build process is completed, the FDM built part can be viewed as a laminate composite structure with anisotropic material properties. The fabricated part takes the form of a laminate composite with vertically stack layers, each of which consists of contiguous material fibres or raster width interstitial voids. Fibre-to-fibre bonding within and among layers occurs by a thermally-driven diffusion bonding process during solidification of the semi-liquid extruded fibre [2,7,9,10,12,31].
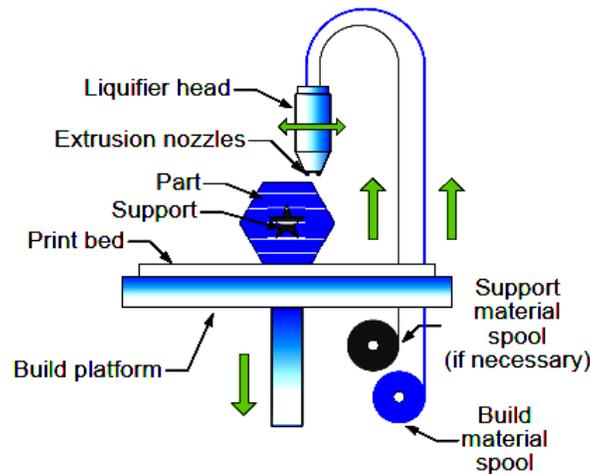
Figure 1: Schematic of FDM process [2, 14].

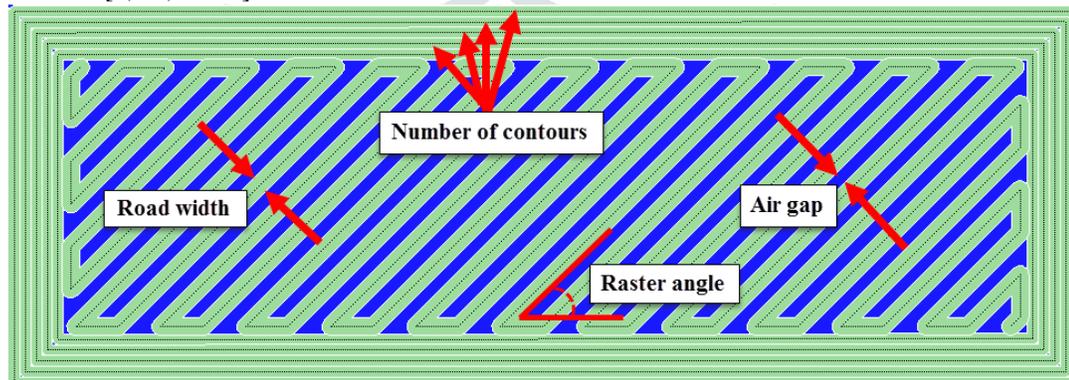*a. FDM Process Parameter* [2, 12, 13-17]**:**

Figure 2: FDM tool path parameters [2, 13, 18].

Table 1: Process parameters in FDM

Process Parameter	Definition
Part fill style	Determines the fill pattern used to build a solid model. It is of two types: ☐ Perimeter/rasters: Creates a part fill consisting of a single outer contour and internal raster fill. ☐ Contours to depth: Fills the part with an outer contour, internal contours, and internal raster fills. The number of additional contours is determined by the depth of contours value
Contour width	The width of the contour tool path that surrounds each of the part curves. Every part curve is filled by using at least one contour.
Part interior style	Choose the manner in which part interior is filled. It is of three types: ☐ Solid normal: Fills the part completely. ☐ Sparse: Minimize the amount of material use. Utilizes a unidirectional rasters. ☐ Sparse double dense: minimizes the amount of model material used, but utilizes a crosshatch raster pattern (instead of uni-directional) for added strength.
Visible surface	The intent of this feature is to maintain part appearance while allowing for a coarser, faster fill. The default choice is Normal rasters.
Part XY shrinkage factor	The shrinkage factor applied in the XY plane.
Part Z shrinkage factor	The shrinkage factor applied in the Z direction.
Perimeter to raster air gap	The gap between the inner most contour and the edge of the raster fill inside of the contour.
Layer thickness	It is a thickness of layer deposited by nozzle and depends upon the type of nozzle used.
Orientation	Part build orientation or orientation refers to the inclination of part in a build platform with respect to X, Y, Z axis. X and Y-axis are considered parallel to build platform and Z-axis is along the direction of part build.
Raster angle	It is a direction of raster relative to the x-axis of build table.
Raster width	Width of raster pattern used to fill interior regions of part curves
Air gap	It is the gap between two adjacent rasters on same layer.

b.   Common materials used in FDM [2-4, 20, 21]**:**

FDM parts are tougher and more durable than those produced by SLA. FDM materials allow you to manufacture real parts that are tough enough for prototyping, functional testing, installation, and most importantly -end use. Real production thermoplastics are stable and have no appreciable warpage, shrinkage, or moisture absorption, like the resins (and powders) in competitive processes. Because thermoplastics are environmentally stable, part accuracy (or tolerance) doesn't change with ambient conditions or time. This enables FDM parts to be among the most dimensionally accurate. Basic FDM materials (thermoplastic): ABS plus, ABS-M30, ABS-M30i, ABSi, PC-ABS, PC, PC-ISO, PPSF/PPSU (polyphenylsulfone), ULTEM 9085.

3.   Literature Survey:

Analysis of past research suggests that part quality of FDM parts relates to part strength, surface quality and dimensional accuracy and it depends significantly on few primary control factors such as layer thickness, deposition direction of filament roads, road (or raster) width, gap sizes between filaments and stacking sequence of the vertically stacked layers of bonded fibers (roads) [5]. There are significant variations in geometry and properties among identical parts built on different machines. The research work in fused deposition modeling is done considering different machine, material and process parameters. The researchers have done work on different FDM machines such as FDM Vantage SE machine [6, 9-11, 24], Stratasys Fortus 400mc [7, 13, 22, 25, 35], FDM 3000 [16, 18], Fortus 250 mc [28, 29], Dimension BST 1200 [31, 33], Fortus 900 mc [26], etc. with different specimen materials like ABS [5, 14-17, 19, 20, 27, 30, 32-34] , ABS P400 [6, 9-11, 21, 24, 31], ABS P430 [28, 29], Polycarbonate [13, 25], ABS M30i [22, 23, 26, 35], ABS M30 [3], etc. In the research work they have considered the process parameters like layer thickness, orientation, raster width, raster angle, air gap, etc. for studying the dimensional accuracy [3, 7, 9, 21, 32], surface roughness [3, 14, 15, 17, 22, 23, 25, 32, 35], mechanical properties [4-6, 8, 10, 12 - 14, 21, 23, 24, 25, 31, 34], material volume, time, cost [21, 25, 28, 29, 30, 33]. To study the output parameters they have used Taguchi Method [3, 9, 16, 20, 22, 25, 30, 32, 35], ANOVA [10, 16, 20, 22, 24, 30, 32, 35], Artificial Neural Network (ANN) [6, 9, 11], Response surface plots [6, 10, 28, 29], quantum-behaved particle swarm optimization (QPSO) [6, 11], I-optimality criterion for the optimization [7], Bacteria Foraging Optimization Algorithm (BFOA) [24], multiple regression approach [22, 25] and TLBO Algorithm [36].

a.   Critical Review of References:

Table 1: Comparative study between process parameters and output parameters

		Process Parameters					
		Layer Thickness	**Orientation**	**Raster Width**	**Raster Angle**	**Air Gap**	**Ref. No.**
	Build Time (less)	0.254	0 & 45	0.5064		Positive	**1, 24, 26, 29**
	Support Material (less)	0.254					**24**
	Part Material (less)	0.254	0	0.4064	0	Positive	**24, 28**
	Surface Roughness (less)	0.127	0	0.4064	90	0 or Negative	**1, 2, 3, 21, 22, 24, 31**
Dimensional Accuracy	**Length**	0.254	0	0.4564	60	Positive	**6, 8, 31**
	Width	0.254	0	0.4564	30	Positive	**6, 8, 31**
	Thickness	0.127	0	0.5064	0	Positive	**6, 8, 31**
Mechanical Properties (More)	**Tensile**	0.254	0	0.4064	90	0 or Negative	**3, 5, 9, 11, 20, 22, 23, 25, 33**
	Flexural	0.127	0	0.4064	90	0 or Negative	**5, 9, 20, 23, 33**
	Impact	0.254	0, 30	0.5064	90	Negative	**9, 23**
	Compressive	0.254	0	0.4564	90	0	**9**
	Cost (less)	0.254	0, 90			Positive	**20, 26, 27**

*(Left margin label: **Output Parameters**)*

When material is extruded from nozzle, it cools from glass transition temperature to chamber temperature causing inner stresses to be developed due to uneven deposition speed resulting in inter layer and intra layer deformation that appear in the form of cracking, de-lamination or even part fabrication failure. These phenomena combine to affect the part strength and size. It has been observed that deformation is more in bottom layers than upper layers. Higher the stacking section lengths, large the deformations. If chamber temperature increases, deformation will gradually decrease and become zero when chamber temperature equals glass transition temperature of material. Therefore, it is proposed that material used for part fabrication must have lower glass transition temperature and linear shrinkage rate. Also the extruded fibre length must be small. The foregoing discussions reveal that FDM processed parts exhibit anisotropy of mechanical properties. Properties are sensitive to the processing parameters because parameters affect meso-structure and fibre-to-fibre bond strength. Also uneven heating and cooling cycles due to inherent nature of FDM build methodology results in stress accumulation in the built part resulting in distortion which is primarily responsible for week bonding and thus affect the strength and volumetric shrinkage [2, 12, 15-17].

Number of layers in a part depends upon the layer thickness and part orientation. If number of layers is more, it will result in high temperature gradient towards the bottom of part. This will increase the diffusion between adjacent raster's and strength will improve. But high temperature gradient is also responsible for distortion within the layers or between the layers. Moreover, increase in number of layers also increases the number of heating and cooling cycles and thus residual stress accumulation increases. This may results in distortion, interlayer cracking and part de-lamination or fabrication failure. Hence, strength will reduce. Small raster angles are not preferable as they will results in long raster's which will increase the stress accumulation along the direction of deposition resulting in

more distortion and hence weak bonding. But small raster angle also means that raster's are inclined along the direction of loading and will offer more resistance thus strength will improve. Thick raster's results in stress accumulation along the width of part and have a same effect as the long raster's. But this stress accumulation results in high temperature near the boding surfaces which may improve the diffusion and may result in strong bond formation [2, 16, 30].

Zero air gap will improve the diffusion between the adjacent rasters but may also decreases the heat dissipation as well as total bonding area [16]. Using the optimal part orientation is vital to reduce support material, which will lead to reduce building time and improve the surface finish [28].

4. Advantages of FDM in Comparison to Other Technologies:

It can economically build custom products in small quantities as if mass production were used. Sources of cost effectiveness include: No need for costly tools, molds, or punches, No scrap, milling, or sanding requirements, Automated manufacturing, Use of readily available supplies, Ability to recycle waste material, Minimal inventory risk as there is no unsold finished goods inventory, Ability to easily share designs and outsource manufacturing, Speed and ease of designing and modifying products.

5. Important FDM Applications:

Automotive, Manufacturing, Medical, Recreational, Jewelry, Aerospace, Education, Dental, architecture, construction (AEC), industrial design, military, biotech (human tissue replacement), fashion, footwear, eyewear, geographic information systems, food, and many other fields.

6. Conclusion:

a. The best combinations for minimization of % change in length are maximum layer thickness, raster angle, air gap, minimum orientation, and medium raster width, maximum. For minimizing the % change in width, it requires medium raster angle and air gap. For lower thickness it requires minimum layer thickness, orientation, raster angle, and maximum value of raster width and air gap.

b. The minimum surface roughness value is obtained by minimum layer thickness, orientation, raster width, air gap and maximum raster angle.

c. The best combinations for maximum tensile strength are maximum layer thickness, raster angle and minimum orientation, raster width, air gap. For maximum flexural strength, it requires minimum layer thickness, orientation, raster width, air gap and maximum raster angle. For maximum compressive strength it is required maximum layer thickness, raster angle, medium raster width, air gap and minimum orientation. For maximum impact strength it is required maximum layer thickness, raster angle, raster width and minimum orientation and air gap.

d. These input parameters affect the output parameter drastically. So, a proper trade off should be done according to the output parameter requirement and selecting the process parameters.

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