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A Parametric Study of Additive Manufacturing Process

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Abstract: Additive manufacturing (AM) is a generic term for a number of technologies that enable fabrication of physical objects directly from CAD data sources. In contrast to classical methods of manufacturing such as milling and forging which are based on subtractive and formative principles respectively, these processes are based on additive principle for part fabrication. The biggest advantage of AM processes is that an entire 3-D (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, flexibility, and possibility of producing complex parts and shapes. The major limitation of this process is that performance of prototypes is sensitive to process parameter variation.

Keywords: additive manufacturing, CAD, FDM, dimensional accuracy, surface roughness.

I. INTRODUCTION

Additive manufacturing of physical parts or otherwise known as solid freeform manufacturing or desktop manufacturing or layer manufacturing technology or rapid prototyping, represents the new phase in the evolution of prototyping. The invention of this series of rapid prototyping methodologies is described as a watershed event because of the tremendous time savings, especially for complicated model. Since 1988, more than twenty different rapid prototyping techniques have emerged. It is the automatic construction of physical objects using additive manufacturing technology. The first techniques 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 primary advantage to additive fabrication is its ability to create almost any shape or geometric feature [1-6].

TABLE I: COMPARISON OF ADDITIVE MANUFACTURING PROCESSES [1, 2, 4, 5, 8]

Supply Phase	Process	Layer creation Technique	Phase Change Type	Materials
Liquid	Stereo lithography (SLA)	Liquid Layer Curing	Photo polymerization	Photopolymers (such as acrylates, epoxies, colourable resins and filled resins)
	Fused Deposition Modelling (FDM)	Extrusion of melted polymer	Solidification by cooling	Polymers, Wax
Powder	Three Dimensional Printing	Layer of powder and binder droplet deposition	No phase change	Ceramic, Polymers, metal powder and sand
	Selective Laser Sintering (SLS)	Layer of powder	Laser-driven sintering, melting and solidification	Polymers, metals with a binder, metals, ceramics and sand with a binder
Solid	Laminated Object Manufacturing	Deposition of sheet material	No phase change	Paper and polymers

Additive manufacturing (AM) represents a new edge on the prototyping process evolution. 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 range of applications where this technique can be used is extensive, ranging from medical applications to automotive and aeronautics [1, 2, 4, 5, 8].

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Although several rapid prototyping techniques exist, following is the most popular basic five-step process (Fig. 1).
The steps are:
1) Create a CAD model of the design
2) Convert the CAD model to STL format (.stl)
3) Slice the STL file into thin cross-sectional layers.
4) Construct the model one layer atop another
5) Clean and finish the model [3, 7, 8, 11].

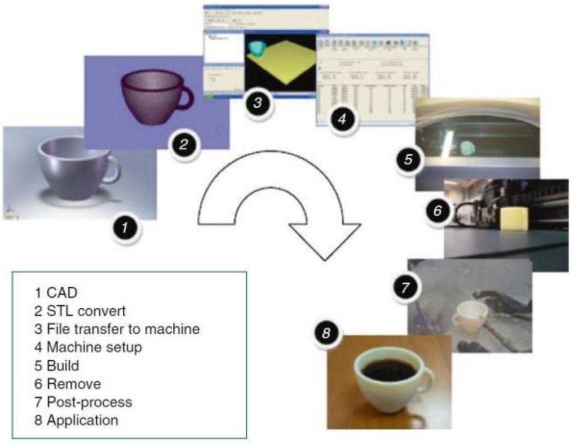


Fig.1: The Basic Process

An increasing number of industries benefit from the advantages of the technologies such as the freedom of design and AM is progressively pushed from rapid prototyping towards small series production. Today, AM is already widely spread within known fields of application for instance within the aerospace and defense (A&D), automotive and electronics industry, and the medical sector including dental applications, prostheses, implants etc. Even, consumer industries such as the sports, the furniture or the jewelry industry are becoming aware of the advantages of AM-technologies for their business [1-7].

II. FUSED DEPOSITION MODELING

Fused deposition modeling, which is often referred to by its initials FDM, is a type of additive fabrication 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 [3, 4-8].

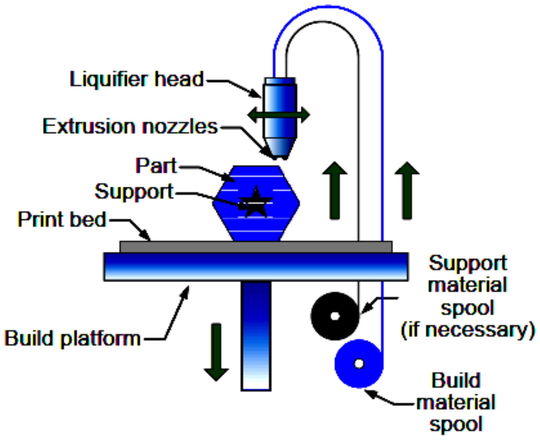


Fig. 4: Schematic of FDM process [12].

But unlike other RP 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 (reel). 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 [7, 9, 10, 12, 31].

The bonding between the individual roads of the same layer and of neighboring layers is driven by the thermal energy of the semi-molten material and diffusion. In FDM, as in other LM processes, the heating and rapid cooling cycles of the work materials will aggravate non-uniform thermal gradients and cause stress build-up that consequently results in part distortions and dimensional inaccuracy. The mechanical properties of FDM parts are not only controlled by the build material, but also influenced by the selected fabrication parameters. 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) [9].

2.1 FDM Process Parameter [10 - 16]**:**

These factors are defined as follows:

1. Orientation: Part build orientation or orientation refers to the inclination of part in a build platform with respect to X, Y, Z axis, where X and Y-axis are considered parallel to build platform and Z-axis is along the direction of part build, Fig.5 (a).

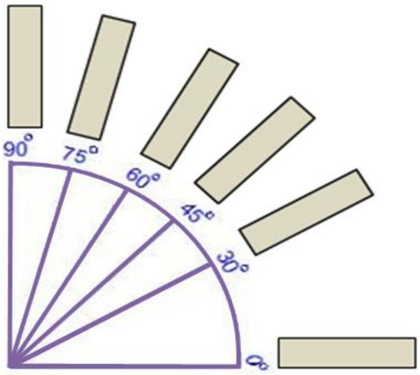
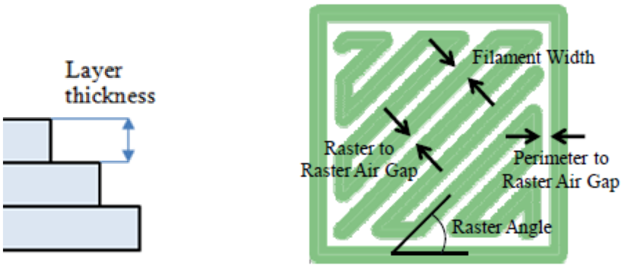


Fig. 5 (a) [11, 16]

2. Layer thickness: It is a thickness of layer deposited by nozzle and depends upon the type of nozzle used Fig. 5 (b).

3. Raster angle: It is a direction of raster relative to the X axis of build table. Specifying the raster angle is very important in parts that have small curves. The raster angles typically allowed are from 0 to 90°. The FDM technique has particular tool paths to fill one part layer. The most used tool path is the raster fill. First the perimeter of the layer is formed by the contour tool paths, and then the interior is filled with a back and forth pattern and an angle of 45° to the x-axis. Alternating layers are filled with a raster direction at 90° to one another, like shown in Fig. 5 (c) [16].



(b) **(c)**

Fig. 5 [11, 16]

4. Part raster width (raster width): Width of raster pattern used to fill interior regions of part curves. Larger values of road width will build a part with a stronger interior. Smaller values will require less production time and material (Fig. 5 (c)).

5. Raster to raster gap (air gap): It is the gap between two adjacent rasters on same layer Fig. 5 (c).

6. Number of contours**:** It is the number of contours built around all outer and inner part curves. Additional contours may improve perimeter part walls.

Although thicker paths lead to a better bonding and thus better mechanical performance, it will most probably fail to meet the geometrical resolution. For the latter purpose, a thin path will ensure shape accuracy in detriment of the mechanical properties [8].

III. LITERATURE REVIEW

Amongst many AM techniques, fused deposition modeling is considered as most appropriate process for RP due to its ease of operation, inexpensive machinery and durability of built parts. The process offers time and cost advantages over conventional technologies. However, the major limitation of this process is that performance of prototypes is sensitive to process parameter variation. This makes it essential to understand the performance of FDM processed parts in relation to variation of process parameters so that the process can be made reliable enough for industrial applications. In order to study the effects of process parameters on surface quality, dimensional accuracy and mechanical properties, earlier research work has been review.

Nozzle diameter: 0.254 mm; since it has been proved to give better results in dimensional accuracy, surface finish and mechanical behaviour than the other possible diameters. The actual size of the extruded filament is larger than the diameter of the tip due to swelling but it can be controlled. Part interior style: Solid – Normal; which fills the interior part completely with fully dense raster tool paths. The extruded angle filaments in the XY plane are +45°/°45° alternating in each layer since it has been proved that parts with this interior style bear better combined loads. Visible surface style: Enhanced; which uses independent controls for the visible surface raster's and the non-visible, internal raster's. The width of the visible raster is smaller than normal in order to improve the surface roughness and the visible appearance. Support style: Breakaway; the removal is easier with this type of support and it is the most used when the parts present complex geometry [17].

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 [10, 13, 14, 15].

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 [14, 28].

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 [14, 28].

Zero air gap will improve the diffusion between the adjacent rasters but may also decreases the heat dissipation as well as total bonding area [14]. Negative air gap (-0.01 mm) and layer thickness (0.254 mm) or raster width (0.508 mm) can be used to reduce surface roughness. Use small layer thickness to increase surface quality. Using the optimal part orientation is vital to reduce support material, which will lead to reduce building time and improve the SF [26].

For minimizing build time, a larger slice height (0.2540 mm), larger road width (0.6604 mm), and positive air gap was more effective. For minimizing support material consumption, a smaller slice height (0.1778 mm), and for minimizing model material consumption, smaller slice heights (0.1778 mm) and positive air gaps are preferred. The optimal top surface roughness value of 7.434 µm was obtained due to some influential process parameters, such as road width of 0.4064 mm, raster angle of 90°, and no air gap. Also, the STL deviation and STL angle process parameters had minimal effect on all performance measures. As such, it is required to make trade-offs either to save on time/ material or to produce a smooth/ rough surface [29].

IV. CONCLUSION

The different process parameters are studied and their effect on the output parameter such as surface roughness, dimensional accuracy and mechanical properties of the part manufactured by the FDM process are understood.

1) Important process parameters studied are layer thickness, raster width, raster angle, orientation and air gap.
2) 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.
3) If the numbers of layers are more, heating and cooling cycle increases and thus accumulation of residual stresses increase. This result in distortion of part, interlayer cracking and part de-lamination or fabrication failure, which affect the output parameter.

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