Advancements in Materials and Parametric Optimization of Fused Deposition Modeling process

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Abstract: Additive Manufacturing has brought a paradigm shift in manufacturing trends in terms of material flexibility, accuracy, lead time and product cost. There are myriad of additive manufacturing technologies which are commercially available but Fused Deposition Modeling (FDM) has outclassed others due to its unique capabilities. The paper aims to present the critical analysis of materials, applications and recent advancements in the area of FDM. The inception of additive manufacturing processes along with their aggressive development in field of new product development and customized parts is also highlighted. A detailed literature survey has been carried out to chalk out various materials and advantages of FDM. An analysis using VOSviewer software has been carried to highlight the major areas where an intensive research has been performed. It has been noticed that limited research has been performed on development of functionally graded material. Moreover, the effect of temperature on different additive manufacturing processes must explored in future.

Keywords: Additive manufacturing, fused deposition modeling, process parameters, materials, optimization

1. Introduction to Additive Manufacturing

An insight for the future is a world full of machines and robots, as the technology in contemporary world is transforming at very fast pace. Significant advancements have been experienced in production industry as manufacturing processes have been completely changed in last 20 years. Additive manufacturing (AM) are a set of digital manufacturing processes which have completely revolutionized the manufacturing industry as tremendous research has been done on them to improve their results. In manufacturing industries, there has always been a demand of low cost, less time-taking and precise processes. [1] All AM processes have potential to overcome these challenges and hence, Rapid manufacturing technologies are the solution for converting our concepts into the real product [2].

AM is a technique of plastic forming and also known as the layered manufacturing, solid freeform manufacturing, 3d printing and rapid prototyping [3]. AM processes are numerically controlled and completely automated with minimum human interference [4]. This technique was first introduced for prototyping but with the technological advancements, these days, it is used for the manufacturing of different functional parts [5]. AM is one of the important technology and is used for making functional prototypes in short time and for analysis for the final product [6]. AM have potential applications due to its ability to create highly complex parts in lesser time with a very minimal cost. [7] This manufacturing technology has completely replaced the use of conventional tools like fixtures, jigs, dies and it has helped in reducing the human intervention to a greater extent and further resulted in increasing the precision of the manufactured product [8].

There are different AM technologies present these days which are capable of processing a wide range of categories of work materials and they are being used in almost every manufacturing sector [9-11]. The introduction of AM has removed the geometric restrictions [12]. FDM is one of the technologies that are widely used because of being the most economical process [13] These days AM technology is being used widely in bio-medical, automotive, aerospace and electronics industries. [14-16]. The detailed process flow chart is shown in Figure 1.

Presently, there are more than 40 AM commercially available techniques which include Stereolithography, selective laser sintering, fused deposition modelling, three-dimensional printing, laminated object manufacturing, profile edge laminae, laser melting, material jetting, ultrasonic additive manufacturing (UAM) and digital light processing [9].

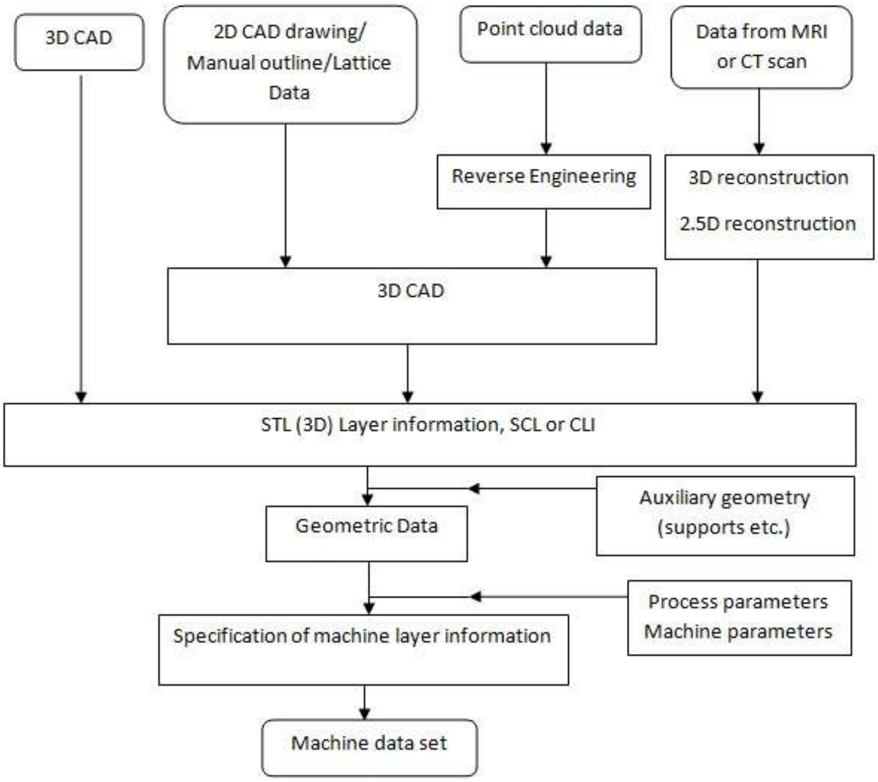


Figure 1 Additive Manufacturing Process flow chart

2. FDM PROCESS

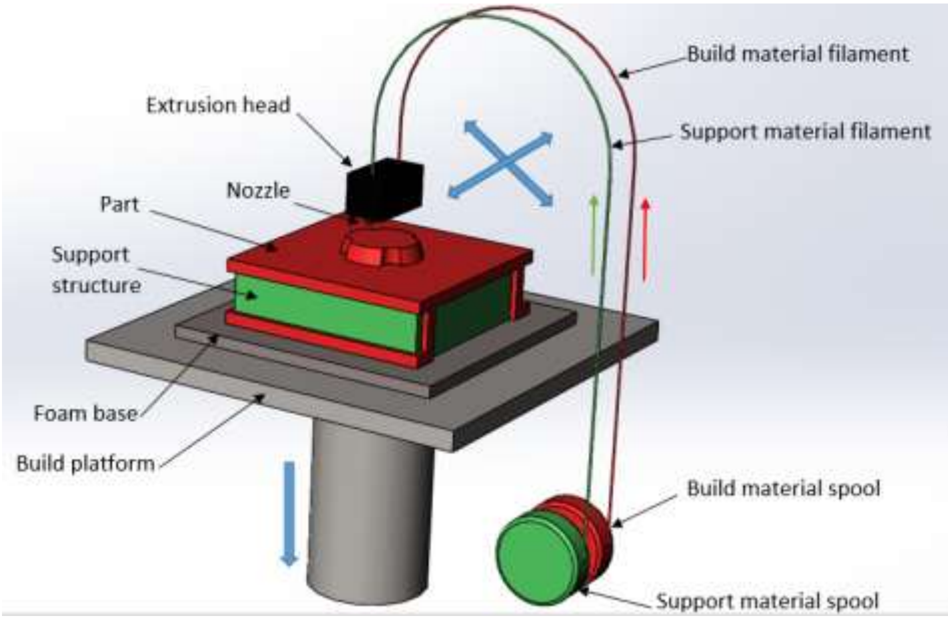
Fused Deposition Modelling (FDM) is one of the emerging AM processes which uses the computer-aided design technology and provides the flexibility of using different material and fabricate complex design with desired accuracy. FDM was developed by S. Scott Crump and patented by Stratasys Inc., USA in the 1990s. FDM is one of the simplest, portable, eco-friendly and cost-effective techniques of additive manufacturing. Moreover, amount of waste produced during the FDM is minimum as compared to other additive manufacturing techniques [10]. These days FDM is one of the most important topics for researchers as different studies have been performed to increase its efficiency. FDM is used for the bridging the gap between the conceptualization and realization [11]. In the FDM process the physical object is created by the CAD model using the layer-by-layer deposition of polymer material extruded from a nozzle [12]. FDM is widely used in industries these days because it is safe, durable and efficient operation and ability to process complex geometries and further useful in converting the concept to the real prototype [13].

FDM is the material extrusion-based process. In FDM there includes the integration of CAD, Material Science and Computer Numerical Control (CNC) during the extrusion process. Using the integration of all the processes, the 3d part is fabricated directly from the CAD model. Basic FDM process includes a plastic filament to be drawn into a liquefied head further this filament is heated up to semiliquid state and then this is extruded through the nozzle. The heads are moved in XY direction and are controlled by the CNC method as shown in Figure 2 [12].

The four basic stages in FDM technology are [18]:

a) Modelling on CAD software
b) Pre-processing
c) Fabrication of Part on FDM machine
d) Removal of support from Fabricated Products (Post-processing)

The very first process of FDM is to create a solid model on CAD software and further, it is converted into stereolithography (STL) format. Then this STL file is pre-processed in the FDM software. Preprocessing in FDM includes the determination of part orientation, selection of FDM parameters, dividing the model into different layers and then finally the generation of supports for it. Mostly FDM process parameters include the raster angle and width, air gap, size of the nozzle tip, temperature, etc. and these parameters depends upon the



type of FDM machine used. This preprocessing is done for every layer of the model individually. For each layer, the FDM software generates the "tool path" for the movement of head. The preprocessed file generated by the FDM software (STL file) is sent to the FDM machine for part building.

Figure 2 Schematic Fused Deposition Modeling

The feedstock filament of FDM machine is drawn from the spool into the FDM liquefier head by drive wheels. Inside it, feedstock filament is heated up to semiliquid state and then extruded out of as ultrathin beads from the nozzle tip. For support, the feedstock filament is drawn from another spool as shown in Figure 2. The head moves according to the CNC program. Material is made by the layer by layer and the material is solidified immediately it comes out of the nozzle. After the process is completed the support structures are removed by breaking them.

3. Process Parameters of FDM

Depending upon the machines, different process parameters can be used to control different characteristics like size, surface, shape, internal structure, etc. These process parameters affect the build quality and time. Some of the main FDM process parameters are layer thickness (slice height), model tip diameter, raster angle, raster air gap, part interior style, raster width, part fill style and the build time. These parameters are needed to be changed during the pre-processing of the STL file on FDM software [19-20]. Some of these important parameters are:

3.1 Slice Height: It is the layer thickness of the part. Or in the coordinate system layer thickness is the distance travelled by the head in the z-direction. Slice height has a direct effect on the build time. Thin layer requires more build time and provides an improved surface finish.

3.2 Model Tip Size: It is the diameter of the tip of the nozzle from where material passes through. This tip is further attached to the liquefier head.

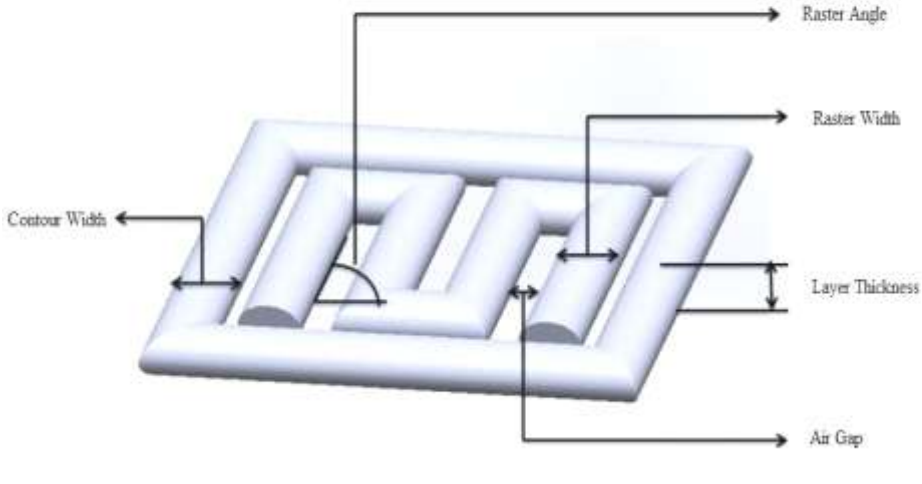
3.3 Model Build Temperature: It is the temperature of the heating element. This temperature controls the material that passes through the liquefier head.

3.4 Raster Width and Raster Angle: Raster width is the width from model tip to layer. It varies according to the FDM machine. Raster angle is the angle between the x-axis and the tool path. The Raster angle and width are shown in Figure 3.

3.5 Part Fill Style and Part Interior Style: Part fills style shows the pattern of filling of material. And Part interior style shows the orientation of interior pats. It determines the amount of air gap between the tool paths.

4. Common Materials used in FDM Process

With the technical advancements the FDM machines, the advanced materials are used such as composites and Nano fillers in polymers. Some of the materials are ABSplus, ABSi, PC, PC/ABS, PPSF, ULTEM, Nylon, investment casting wax and elastomer. The major criteria for selecting a material is that their melting point should lie within the temperature ranges of FDM liquefier head [20]. These days there are a variety of high strength engineering materials available which are the requirement of the FDM process. Maximum



FDM machines use some form of Acrylonitrile Butadiene Styrene (ABS) thermoplastic [20]. The property of standard ABS plastic is high strength and corrosion-resistant. This plastic ABS material is also cheaper compared to other plastic. The main benefit of using this material is that it can be easily machined and finished without altering its strength. These materials should be sufficiently resistant to the heat, chemicals and moistures. ABS plastic also provides various colour options [21].

Figure 3 Various parameters of FDM process

Thermoplastics are one of the most environmentally stable materials. There is the minimal effect of ambient condition on the processed part. Because of this property FDM is considered to be one of the most dimensionally accurate material. Some of the basic FDM materials are [22]:

4.1 ABSplus Thermoplastic: It is one of the commonly used FDM material. It is one best production-grade material and the ideal material for turning the conceptualization to the idealization. This material is environmentally stable and there is no appreciable warpage or shrinkage due to the absorption. Compared to standard ABS material, it is 40% stronger.

4.2 ABS-M30 Thermoplastic: These materials are considered because of their higher tensile strength and recover rapidly under the impact. These materials are considered to be more durable. These are ideal materials for functional prototyping and manufacturing tools. Compare of other standard ABS material they are 25% to 75% stronger depending upon composition. Part processed using this material have high bonding between their layers.

4.3 ABS-M30i Thermoplastic: This is a high strength material which has a potential application in Medical, pharmaceuticals and food packaging industries. The major benefit of the material is that these materials are biocompatible (ISO 10993). This is highly compatible with the parts which require high strength and sterilization. These materials can be sterilized using gamma radiation or ethylene oxide.

4.4 ABSi Thermoplastic: These materials are the translucent material. They are ideal for monitoring material flow and light transmission. These are most commonly used for automotive and biomedical applications. It is available as translucent, natural red and amber colors. They have very good mechanical and aesthetic properties.

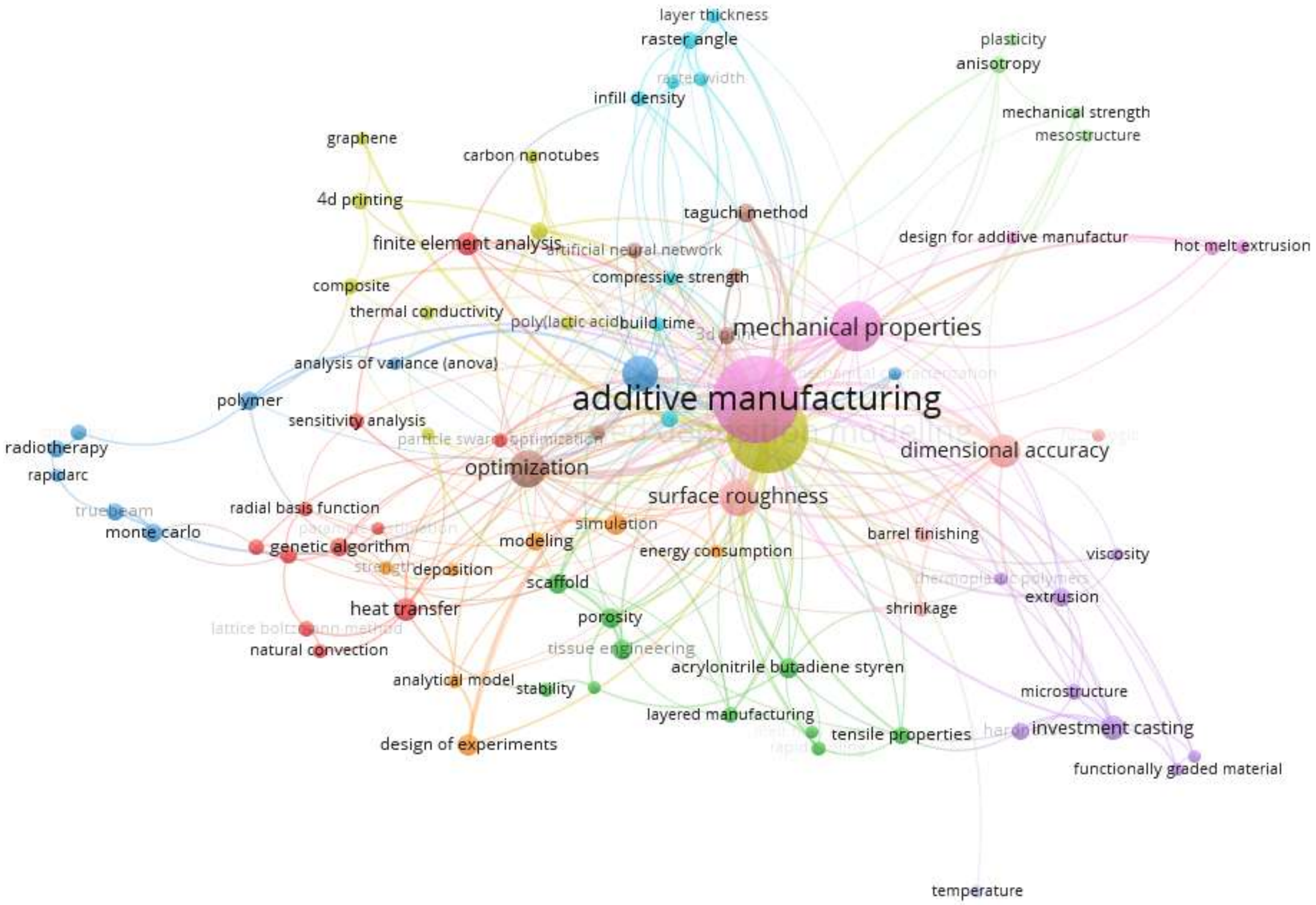
4.5 PC (Polycarbonate) Thermoplastic: These materials are the most widely used in industries. These materials are very much accurate and durable. They are stable and suitable for strong parts. They have a very superior heat resistant and potential mechanical properties. They have a very high tensile strength and can handle the high temperature.

4.6 PPSF (polyphenylsulfone) Thermoplastics: They are the material with the highest heat and chemical resistance. Because of these properties, they are ideal for biomedical, automotive and aerospace industries. They have the highest heat resistance and good mechanical strength. They also provide resistance to petroleum and solvents. It is also sterializable by gamma rays and autoclave.

4.7 ULTEM 9085: This thermoplastic was introduced basically for the aerospace industry and because of its exceptional properties it has application in marine industries also. ULTEM 9085 has very high strength. It has flame retarding properties. This is certified material for use in the aerospace industry because of its exceptional properties. It has V-Zero rating for FST (Flame, Smoke and Toxicity), high strength to weight to ratio. Since it is certified to be used in commercial aircrafts this makes it easy to be used.

5. Visualization Network Analysis

The visualization network chart has been studied to identify the critical research areas explored by researchers in last ten years in areas of materials and parametric optimization of AM (Figure 4). The keywords analysis has been performed using Scopus database related to advancements and research in Additive Manufacturing processes. The extracted data has been analysed using VOSviewer software to perform visualization network analysis. It can be noticed from graph that most of the research has been performed on surface roughness, dimensional accuracy, mechanical properties and optimization of process parameters. A limited research has been performed on the temperature and functionally graded materials.



The future research must be focussed on unexplored areas which may provide wide range of applications. The applications of functionally graded materials in electronics, sensors, aerospace technology must be explored and research must be performed accordingly.

Figure 4 Keyword analyses chart for additive manufacturing

6. Conclusions

Fused Deposition Modelling process is the most widely used process for the additive manufacturing these days. From study it was found that it is the economic and most efficient process for additive manufacturing. This FDM technology has been extensively used in almost every manufacturing industry because of its simple and low waste production method. These days, apart from prototyping, they are now used for functional and end-product fabrication. There are different materials available for the manufacturing using FDM process. The study has been conducted to investigate different materials used for various applications along with and major parameters which affect the accuracy of process. These materials are extensively used in research and development to change their conceptual idea into a real model or product. Further, it was found that with implementation of AI and ML can improve the FDM process to a great extent. They have a potential application in the field of functionally graded materials, biomedical, electronics and aerospace engineering.

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