Materials Forming, Machining and Tribology

Harshit K. Dave
J. Paulo Davim *Editors*

Fused Deposition Modeling Based 3D Printing

Springer

Materials Forming, Machining and Tribology

Series Editor

J. Paulo Davim, Department of Mechanical Engineering, University of Aveiro, Aveiro, Portugal

This series fosters information exchange and discussion on all aspects of materials forming, machining and tribology. This series focuses on materials forming and machining processes, namely, metal casting, rolling, forging, extrusion, drawing, sheet metal forming, microforming, hydroforming, thermoforming, incremental forming, joining, powder metallurgy and ceramics processing, shaping processes for plastics/composites, traditional machining (turning, drilling, miling, broaching, etc.), non-traditional machining (EDM, ECM, USM, LAM, etc.), grinding and others abrasive processes, hard part machining, high speed machining, high efficiency machining, micro and nanomachining, among others. The formability and machinability of all materials will be considered, including metals, polymers, ceramics, composites, biomaterials, nanomaterials, special materials, etc. The series covers the full range of tribological aspects such as surface integrity, friction and wear, lubrication and multiscale tribology including biomedical systems and manufacturing processes. It also covers modelling and optimization techniques applied in materials forming, machining and tribology. Contributions to this book series are welcome on all subjects of "green" materials forming, machining and tribology. To submit a proposal or request further information, please contact Dr. Mayra Castro, Publishing Editor Applied Sciences, via mayra.castro@springer.com or Professor J. Paulo Davim, Book Series Editor, via pdavim@ua.pt.

More information about this series at http://www.springer.com/series/11181

Harshit K. Dave · J. Paulo Davim
Editors

Fused Deposition Modeling Based 3D Printing

Springer

Editors
Harshit K. Dave
S. V. National Institute of Technology
Surat, India

J. Paulo Davim
Department of Mechanical Engineering
Campus Santiago
University of Aveiro
Aveiro, Portugal

ISSN 2195-0911 ISSN 2195-092X (electronic)
Materials Forming, Machining and Tribology
ISBN 978-3-030-68023-7 ISBN 978-3-030-68024-4 (eBook)
https://doi.org/10.1007/978-3-030-68024-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

3D printing is the common term used for a variety of additive manufacturing processes in which a three-dimensional object is constructed using a CAD model. Earlier, this process was considered suitable for producing prototypes only. However, in recent times, with the improvement of precision and repeatability, few of the 3D printing processes have become viable as an industrial production technology. Fused deposition modelling is a term used for the 3D printing process, wherein a continuous filament is fed from a spool through a hot extruder head and deposited layer by layer. FDM-based 3D printing is, at present, the most popular 3D printing process owing to its cost and flexibility. Other 3D printing techniques may offer better results, but they are far costlier than the FDM process.

An attempt has been made in this book to provide a thorough understanding of the FDM-based 3D printing process followed by recent studies on experimental investigations, specific applications as well as modelling and optimization of the process. The book consists of 25 chapters. The first two chapters of this book provide a basic outline of the FDM-based 3D printing process. These include the full description of the technique, types of machines and raw materials, process parameters, defects, design variations and simulation methods. The next six chapters (third to eighth chapters) include a vast range of experimental investigations that include studies on process improvement, microstructure study, mechanical testing and characterization. The post-processing of 3D printing part is an important stage of preparing functional parts. The next two chapters (ninth and tenth chapters) are dedicated to the post-processing stage of 3D printing. As 3D printing substantially reduces waste, it is considered to be better in enhancing the sustainability of the products than most of the other existing manufacturing processes. There are two chapters (eleventh and twelfth chapters) dedicated to sustainability concerns in the FDM process. There are wide-scale applications of the FDM process in 3D printing ranging from composites to health care and electronics applications. Seven chapters (thirteenth to nineteenth chapters) discuss various applications like composites, external medical devices, drug delivery system, orthotic inserts, watertight components, etc. Specifically, the nineteenth chapter is dedicated to 4D printing using the FDM process. Though 3D printing is widely used in present days, the understanding of the theoretical aspects through modelling and optimization is finding immense interest. The last six chapters (twentieth to twenty-fifth chapters) are exclusively dedicated to modelling and optimization study of the FDM process. There is an interesting discussion on computational models, evolutionary algorithms, tool path optimization, layout optimization along with the application of machine learning and metaheuristic approaches in the FDM process.

This book is primarily aimed at graduate-level researchers and educators studying 3D printing. There is sufficient depth for research students with many references to provide direction towards their chosen research area. Researchers will also benefit from the book to know about opportunities for further research.

We are sincerely thankful to Springer for providing this opportunity as well as their professional support throughout the process. Last but not the least, we extend our heartfelt gratitude to all the contributors for their valuable contributions to this book especially during the pandemic situation all around the world which largely restricted access to our laboratories and other resources.

Surat, India Harshit K. Dave
Aveiro, Portugal J. Paulo Davim
April 2021

Contents

Introduction to Fused Deposition Modeling Based 3D Printing Process

Harshit K. Dave and Sandip T. Patel

Abstract Fused deposition modeling (FDM) or fused filament fabrication (FFF) is one of the most popular 3D printing technologies for variety of applications. It's ease of use and affordable cost makes it popular among diverse group of users. In this chapter basics of FDM technology is discussed to cater all types of readers. The process parameters and its effects are also included in this chapter.

1 3D Printing

3D printing (3DP) is commercially existing from 80's, but still today it resembles technology from the science fiction movie. Today 3D printers have begin to enter into household as an essential article, similar to computer.

Another accepted technical term for 3DP is additive manufacturing (AM). According to ISO/ASTM [1], 3DP is defined as process of joining material feedstock to make desired shape part from 3D model data, usually layer upon layer. In this definition, feedstock means bulk raw material and layer means process of laying out the feedstock material to create a surface. The shape of layer is generally planar in order to reduce complexity of much complex 3DP procedure. Addition to this, it is worth mentioning that layer should be adequately thin. 3D model data requirements render computer essential for 3DP, unlike subtractive- and formative-manufacturing.

H. K. Dave
Department of Mechanical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India
e-mail: harshitkumar@yahoo.com

S. T. Patel (✉)
Department of Mechanical Engineering, Government Engineering College, Valsad, Gujarat, India
e-mail: stpatel1983@gmail.com

H. K. Dave and J. P. Davim (eds.), *Fused Deposition Modeling Based 3D Printing*, Materials Forming, Machining and Tribology,
https://doi.org/10.1007/978-3-030-68024-4_1

There are many well-established 3DP processes exist today and still new processes are getting invented and developed. Principle difference between these processes lies in two operations:

i. how layer of feedstock material is created, and
ii. how subsequent layer are bonded or fused

These operations mainly depend on type of feedstock material (i.e. metal, polymer, ceramics, composite etc.) and form of feedstock material (i.e. powder, sheet, filament, liquid, slurry, paste etc.). All these factors determine the working principle and machine architecture of particular 3DP process. Based on fundamental working principle, 3DP processes can be broadly categorised into seven types as depicted in Fig. 1.

2 Material Extrusion

According to ISO/ASTM 52900:2015 [1], material extrusion is the umbrella term for 3DP processes in which material is selectively dispensed through a nozzle or orifice to build parts. In simple terms, it is analogous to computer controlled hot glue gun used to build three-dimensional shape by dispensing glue layer upon layer.

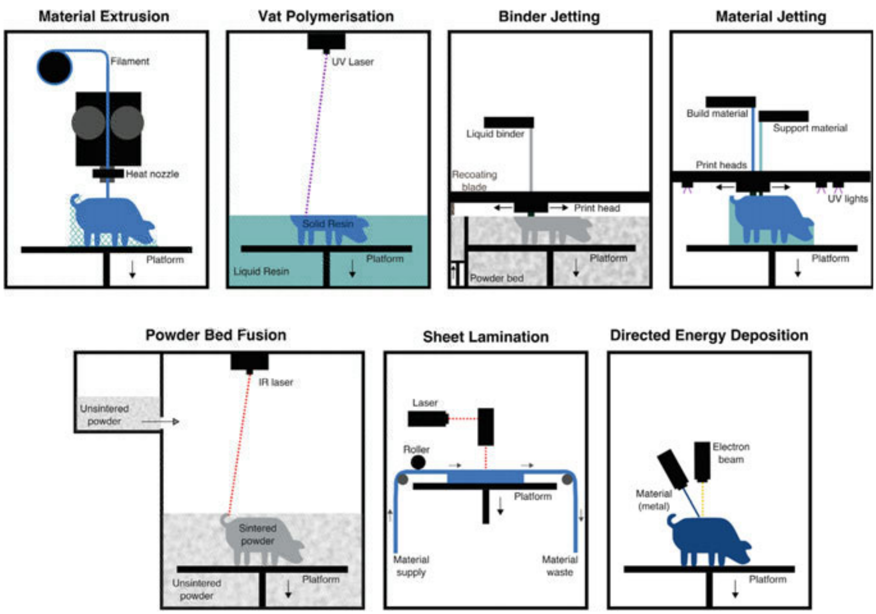

Fig. 1 Illustrations of the seven categories of 3DP processes (Image permission under the Creative Commons Attribution License 4.0 [2])

Extrusion in conventional manufacturing is forming operation to create uniform cross section objects by continuously pushing out heated material through die. The shaping of object finalizes when material came out of a die. Material extrusion in context of 3DP is not related to forming, as shaping of object is not finalized when material is pushed out of nozzle. Object shape is finalized by in situ deposition of material as per the CAD data. The continuous strand of material came out of nozzle gives distinguish characteristic to the object, which differentiate material extrusion from other 3DP processes.

Material extrusion is generally used for polymer materials. Conceptually any material which can flow continuously out of nozzle and then harden can be used for material extrusion. So, there are variety of materials that can be used such as polymer, polymer matrix composite, clay, concrete, food, hydrogels etc. In theory the same process can be used for metals by heating them at high temperature. Due to high surface tension of molten metal it will form droplets coming out of nozzle and not continuous strand of metal, which cannot be considered as material extrusion.

The sole focus of this book is on the fused deposition modeling (FDM) technology. Thus, rest of the topics are concentrated on FDM technology.

3 Introduction of Fused Deposition Modeling

Fused deposition modeling (FDM) is most prevailing material extrusion type 3DP technology. It is the reason that majority presumes material extrusion as FDM. The term FDM is coined and trademarked by, its inventor and co-founder of Stratasys, Scott Crump. Fused filament fabrication (FFF) is another term used as synonym to fused deposition modeling. The term FFF had coined by the makers of RepRap project [3] and advocated by members of open source community to prevent legal issues related to intellectual property rights (IPR). In this chapter the term FDM is used to be interpreted as FFF/FDM for convenience.

FDM can be defined as filament based material extrusion 3DP process in which polymer (usually thermoplastic) filament is melted using heated nozzle and selectively dispensed layer by layer to build parts [4, 5]. There is no standard definition exist for FDM by national or international standards. Due to this reason, many times other material extrusion techniques are falsely considered as FDM. The distinct feature of FDM is filament based material extrusion, wherein filament also act as a machine element. Solid filament perform function of a piston to push molten material in heated nozzle.

FDM is the most extensively employed 3DP technology in terms of number of 3D printers worldwide actively installed [6, 7]. It is most affordable 3D printing technology at desktop scale, which makes it first choice for domestic consumers, hobbyist and education institutes.

4 FDM Process and Working Principle

Overall FDM printing process is depicted in Fig. 2. Similar to generic 3DP process, it starts with creation of CAD model with aid of any CAD software. The 3D CAD model is prepared by designer using design inputs and in case of reverse engineered design, using scanned data of a geometry. Then native CAD model is converted into file format which can be understood by 3D printing software, commonly known as slicing software. These common file formats are respectively STL, OBJ, AMF and 3MF. The STL format is the most used file format. It has become unofficially accepted standard representation in the 3DP industry [8].

In next step, the tessellation CAD model is imported in slicing software. Nowadays, few commercially available slicing software are capable of importing native 3D files from CAD software, which improves the accuracy of CAD model. Slic3r, Cura and Repetier are few popular and freely available slicing software. The main function of slicing software is to convert imported 3D CAD models into printing instructions for a given 3D printer to build an object. The slicing software performs numbers of tasks including: (i) slicing CAD model into thin horizontal layers, (ii) infill generation, (iii) support structure generation for overhangs, and (iv) tool path generation for each layer; based on user inputs for build orientation, slicing parameters (i.e. raster width, raster orientation, infill, layer thickness etc.) and machine parameters (i.e. deposition speed, extrusion temperature, build platform temperature etc.). All of this necessary process-relevant data to convert a digital model into a physical model is then recorded in the G-code file. This G-code file can afterwards be sent to FDM printer.

The controller unit of FDM printer directs the printhead to build a part with layer by layer deposition of material as per instruction recorded in G-code file. The typical FDM printer schematic is depicted in Fig. 3. During printing, the filament

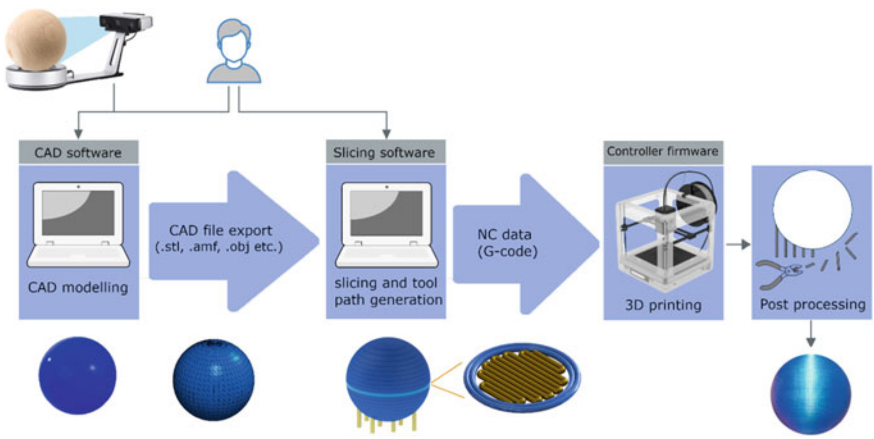

Fig. 2 FDM printing process

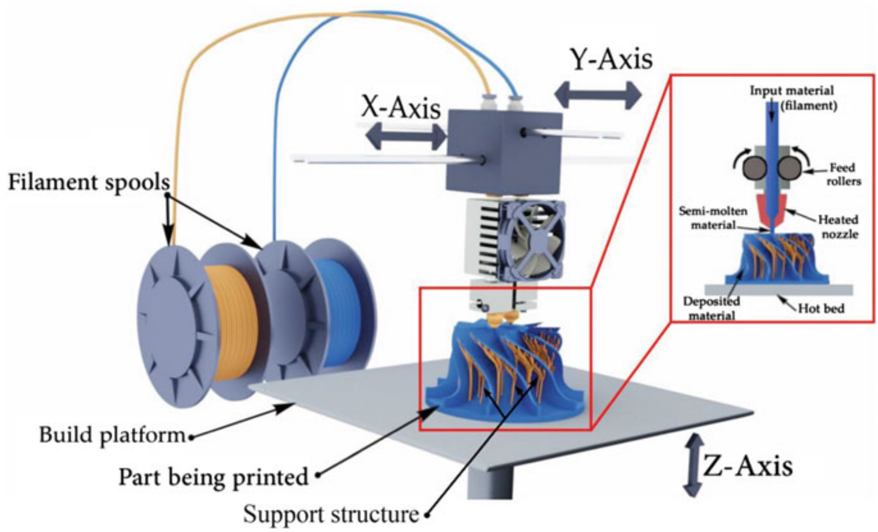

Fig. 3 FDM printer schematic (Image permission under the Creative Commons Attribution License 4.0 [10])

based feedstock material is unwounded from spool and fed to printhead, which heats the filament into semiliquid state above its glass transition temperature. It is then extruded out of a nozzle in form of fine bead and deposited on built platform of printer. Here, moving solid filament perform function of a piston to push molten filament out of nozzle [9]. The force exerted by filament to extrude the melt must be adequate to overcome the pressure drop across the printhead, which depends on the rheological properties of the melted material and the geometry of the flow path. Thus, filament must be rigid enough and should not fail under buckling. Filament acting as a machine element simplifies and reduce the size of extrusion mechanism of FDM printer. The printhead (or the build platform) can travel in X- and Y- axis, which enable depositing the molten material to form 2D layers of the build part. On completion of each layer, starting from the bottom layer, the build platform (or the printhead) will travel in the Z axis by amount of selected layer thickness, which enable depositing the following layer on top of the preceding layer. The hot semiliquid state of the material deposited from the nozzle tip enables adjacent layers and adjacent beads to fuse together. The nozzle tip pressed the extruded molten material against the previous layer. Due to pressure and the high temperature, the surface of the previous layer re-melts. This enables the fusion of the new layer with the previously printed substrates. The material solidifies quickly after being deposited. The layer by layer deposition process is continue until the part is finish. Dual extrusion head printers are also available, in which one nozzle dispense base material to build part while second nozzle dispense material for support structure.

In last step, the completed part is removed from the FDM printer and post processing operations are carried out as per the requirement. Generally, the objective of post processing is to remove support structure, improve aesthetics and improve surface quality. The support structure material is either insoluble or soluble type. Insoluble Support structures are removed by breaking them away, as they are printed in a more fragile state. While, soluble support structure material dissolve in water or specific chemicals, such as PVA (soluble in water) and HIPS (soluble in d-Limonene). Variety of other optional post processing operations which can be performed on FDM printed part are sanding, polishing, painting, metal plating, epoxy coating, dipping, vapor smoothing, etc.

5 FDM Printer Types

Variety of FDM printers are available in different sizes, configuration and mechanisms. Their classification according to configuration and technology source is discussed.

5.1 Printer Types as Per Configuration

FDM printers can be classified into four types according to their configuration viz. cartesian, delta, polar, and robotic arm, as depicted in Fig. 4.

5.1.1 Cartesian FDM Printers

The most common FDM 3D printer configuration is cartesian. This type of printer operates using cartesian coordinate system. The build volume shape is rectangular prism and for that reason shape of build platform is kept rectangular or square. This type of printer has three linear carriages in X-, Y-, and Z- axis to place a printhead in the correct position during printing. This is accomplished by either moving

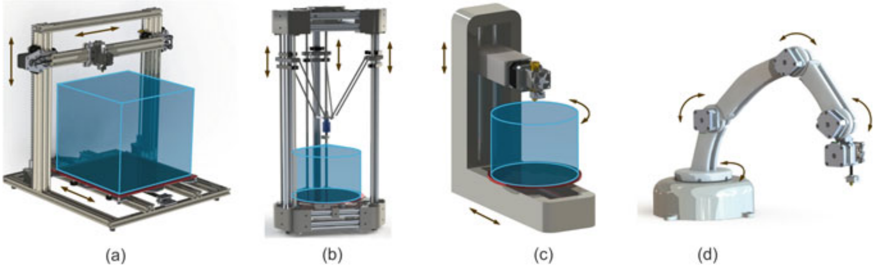

Fig. 4 Types of FDM printers as per configuration, **a** cartesian, **b** delta, **c** polar, and **d** robotic arm, the build volume is shown in blue

printhead or moving both printhead and build platform, driven by linear carriages. There are three popular variants of cartesian 3D printer, as listed below along with example of few 3D printer models available in recent times.

i. Printhead move in X-Y plane and build platform move along Z axis. Examples of 3D printer models: Stratasys F123, Ultimaker S5, MakerBot Replicator+.
ii. Printhead move in X- and Z- axis, while built platform move in Y axis. Examples of 3D printer models: Original prusa mini, LulzBot Mini, da Vinci Jr. 2.0.
iii. Printhead move in X-, Y- and Z- axis, while built platform is stationary. Examples of 3D printer models: BigRep ONE, Cincinnati MAAM.

5.1.2 Delta FDM Printers

Delta configuration 3D printers typically have three arms attached to vertical rails. The printhead is suspended above build platform by these arms in a triangular layout, where the printhead is connected to the end of each arm with spheroidal joints. The coordinated movement of arms on vertical rails adjust the position of printhead relative to the build platform in 3D build envelope. The built platform is kept stationary. The build volume shape is almost cylindrical and for that reason shape of build platform is kept circular.

The delta configuration printers are cheaper and faster but less accurate compared to cartesian configuration printers. Example of popular delta 3D printers are Delta WASP, Anycubic Predator, Mass Portal XD, etc.

5.1.3 Polar FDM Printers

This type of printer operates using polar coordinate system. They are least popular among all other configuration. The build volume shape is cylindrical and for that reason shape of build platform is kept circular. Generally, the printhead can move in Z-axis. The position of printhead is defined by polar coordinate system in horizontal plane, where each point on a plane is determined by a distance from a center point of build platform and an angle from a reference direction. This is achieved by rotating the build platform and linear lateral movement of the build platform (or the printhead). Example of polar configuration printers are Polar 3D and Sculpto PRO2.

5.1.4 Robotic Arm FDM Printers

This category of FDM printer is an industrial robotic arm attached with printhead as an end effector. Robotic arm is more expensive than any other configuration of FDM printer. Still, they are gaining popularity due to their speed and ability to print geometrically complex parts. Example of Robotic arm FDM printers are Dobot Magician and Rotrics DexArm.

5.2 Printer Types as Per Technology Source

There are two types of FDM printer technology available viz. open-source and closed-source. Closed-source or Proprietary technology is closely guarded by means of IPR. As oppose to proprietary technology, open-source technology is freely available for everyone. Under RepRap project many open-source printer designs and its software were developed and available to everyone. On contrary, Stratasys being the pioneers in FDM have the majority of the patent related to FDM and hold on radical technology.

6 Material Feedstock

FDM feedstock is solid filament usually made of thermoplastic material. Filament is characterized by extreme length relative to its uniform cross section. Most commonly available filament diameter sizes are 1.75 and 2.85 mm. There are great variety of materials to choose from and absolutely new materials are emerging regularly in the 3D Printing market. Feedstock materials are available from all category of thermoplastic pyramid including commodity-, engineering- and high-performance- thermoplastics, as depicted in Fig. 5.

As material directly affects the physical properties and printing behavior of printed part, it is important to consider material selection before CAD modeling. The comparison of few popular pure thermoplastic filament material is depicted in Fig. 6. FDM printer filaments available in a variety of polymer material as well polymer based composite consist of fibre- and particle- reinforcement. Variety of reinforcement material can be premixed with thermoplastic to make filament, for example carbon fibre, glass fibre, kevlar, wood, metal powder etc. Continuous fibre reinforcement is also made possible by various similar technology.

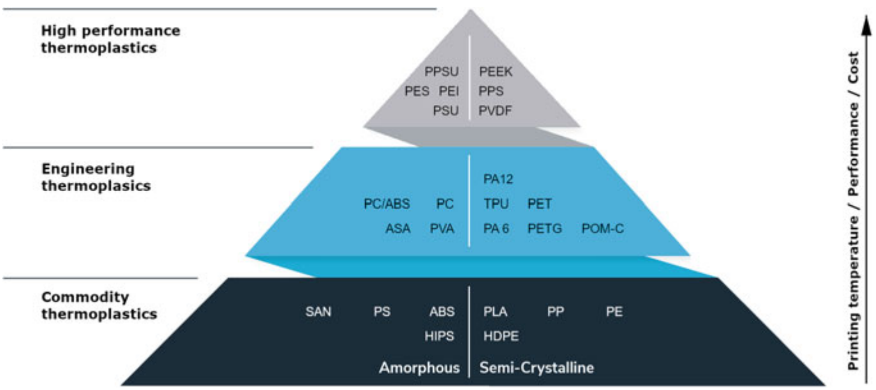

Fig. 5 Thermoplastic material pyramid for FDM filament materials

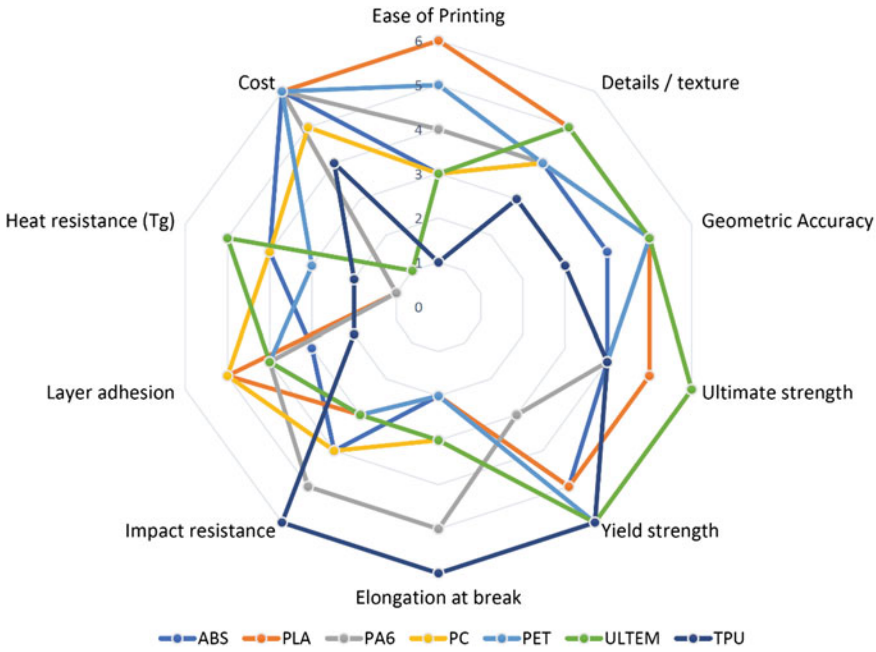

Fig. 6 Ranking of FDM 3D printing polymers on six-point ranking scale (1-being less preferable to 6-being highly preferable) along the different criteria including process-, quality-, thermal- and mechanical- performance

7 Process Parameters

FDM offers various process parameters, and they have a great effect on build time, quality and mechanical characteristics of printed parts [11–13]. Selecting proper combination of process parameters enables predication and control of part characteristics. Which allow the user to select optimum combination of process parameters to achieve part with desired characteristics. These process parameters are related to build orientation, machine parameters (i.e. deposition speed, build chamber temperature, extrusion temperature, build platform temperature etc.) and slicing parameters (i.e. layer thickness, raster width, infill, raster orientation, air gaps etc.) as depicted in Fig. 7.

7.1 Extrusion Temperature

Extrusion temperature is referred to the temperature at which the filament material is heated in the liquefier before extrusion [13].

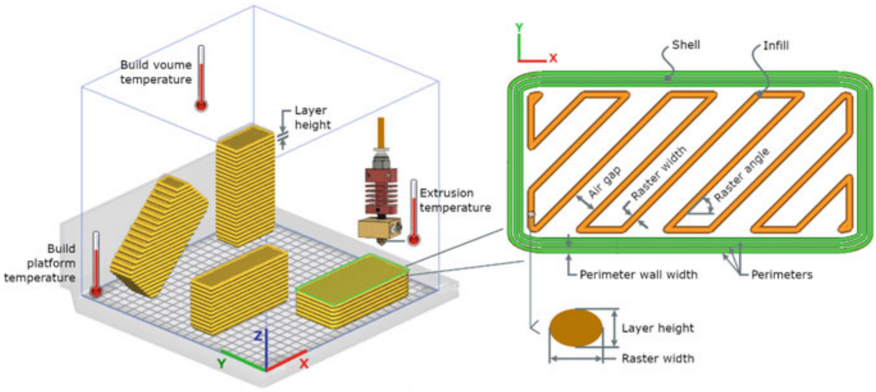

Fig. 7 FDM process parameters

The viscosity of molten material coming out from the nozzle is controlled by extrusion temperature. With increase in extrusion temperature, the viscosity of molten material decreases. This allows melt to flow more easily through the printhead with a smaller pressure drop. Increase in extrusion temperature also improves fusion between successive beads or raster of extruded material, that enhance the mechanical strength of printed part [14]. At higher temperature some polymer degrades quickly and left residue inside the nozzle that would contaminate further melt [15].

7.2 *Nozzle Diameter*

Nozzle diameter is referred to the internal diameter of extruder nozzle opening. Typical nozzle sizes are 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.5, 0.6, 0.8 and 1.0 in mm. It is much obvious that a larger nozzle will extrude more material than a smaller nozzle, hence reduce the build time.

7.3 *Build Orientation*

Build orientation is referred to the orientation of printing part with reference to machine coordinate system in a build envelope, as depicted in Fig. 7.

Build orientation is one of the key process parameter which has significant impact on the staircase effect and volume of support structure generation [4, 17, 18]. Staircase effect is partially responsible for dimensional accuracy and surface finish of printed part. While the support structure generation contribute to post-processing requirement, material amount and build time [17, 18]. An example of support

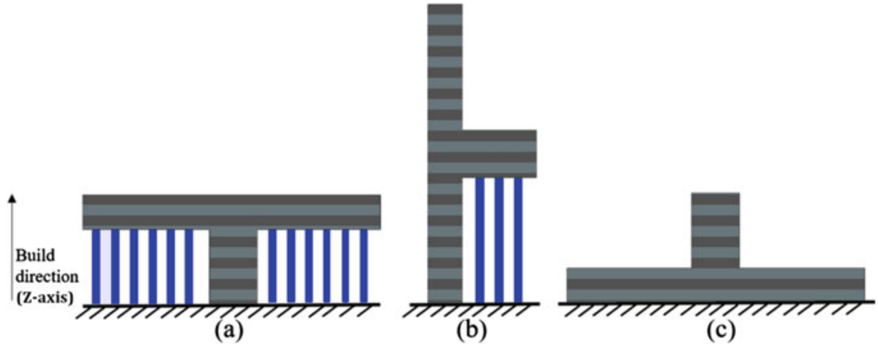

Fig. 8 Support structure (blue) volume requirement for different build orientation of T shaped part (gray): **a** highest, **b** medium, and **c** zero (Image permission under the Creative Commons Attribution License 4.0, adapted from [16])

structure generation for various build orientation of T shaped part is depicted in Fig. 8. Furthermore, build orientation defines the direction in which the mechanical properties of part show anisotropic behavior [18, 19]. This is due to the fact that in FDM, Z-axis anisotropy is highest due to poor inter layer bonding.

7.4 Layer Thickness

Layer thickness is referred to the thickness of the deposited layers along the Z-axis of FDM printer. Typical layer thickness for FDM varies from 0.05 to 0.4 mm [19]. Usually, it is smaller than the printhead nozzle diameter. A rule of thumb suggests, layer thickness should be within 0.25–0.8 times nozzle diameter. The minimum possible layer thickness of FDM printer is called printing resolution on Z-axis or vertical resolution. It is different from printing resolution, which is size of the smallest possible detail on X- and Y-axis.

Layer thickness directly affects surface quality and build time of the printed part. With reduction in layer thickness the staircase effect is minimized, while the build time increases [4, 13]. Smaller layer thickness produced more detailed part having high surface finishing. Furthermore, more precise and accurate slicing of CAD model is made by slicer software for smaller layer thickness, which eventually eliminates potential voids and gaps [19]. It is observed that smaller values of layer thickness enhance the tensile strength [11, 13].

7.5 Raster Width

Raster width is referred to the width of the bead deposited from the nozzle. It depends on the extrusion nozzle diameter, flow rate and print speed. It is observed that smaller values of raster width enhance the tensile strength [11].

7.6 Raster Angle

Raster angle is referred to the angle between the deposition raster and the X-axis of build platform. Thus, Raster angle decides the tool path direction with respect to X-axis of the printer. It should not confuse with raster orientation corresponding to loading condition. The positive direction for raster angle is in anti-clockwise from X-axis.

In reality, combine effect of build orientation and raster angle defines raster arrangement within the part. In simple words, for same layer- and raster-arrangement for a FDM printed part, multiple combination of build orientation and raster angle exists. An example for said condition is depicted in Fig. 9.

7.7 Shell and Associated Parameters

Shell is outermost solid wall of FDM printed parts. Top and bottom wall/shell of part is usually printed by completely filled solid layers. They may be chosen to keep open also.

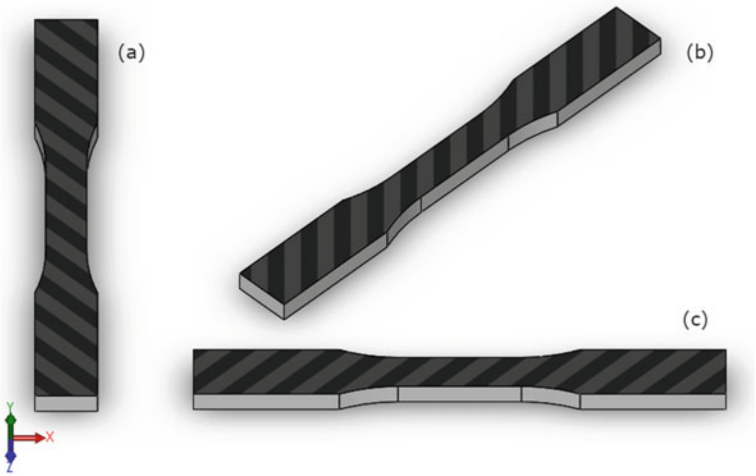

Fig. 9 Tensile test specimens for combination of three build orientations in xy plane and three raster angles viz, **a** 135°, **b** 90°, and **c** 45°; producing same part

The outlines of each layer create the vertical shell. Perimeters is referred to the number of outlines in each layer, which creates vertical shell. While, perimeter wall width is width of the bead deposited in perimeter or outlines in each layer.

7.8 Infill Pattern

In order to decrease build time and save material, FDM parts are generally not printed fully solid. Parts are printed with porous internal structure which is called as infill. The geometry of infill is referred as infill pattern. Selection of infill pattern is generally made based on its printing time, strength and flexibility. Verity of infill patterns are available in various slicer software. There are two types of infill patterns: 2D and 3D. The most commonly used infill patterns are depicted in Fig. 10.

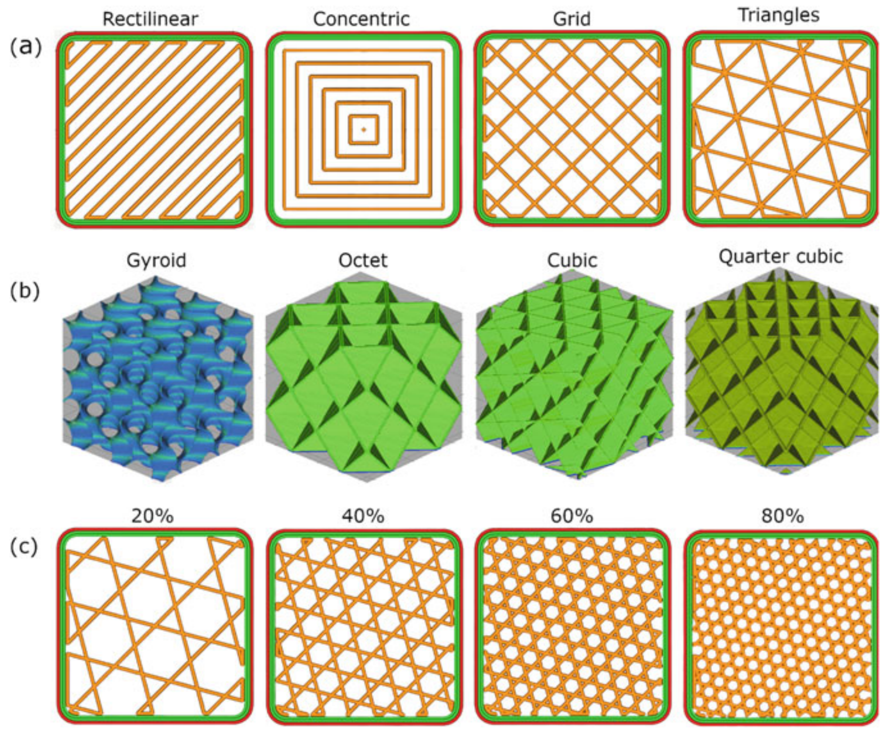

Fig. 10 Commonly found infill types in open software, **a** 2D infill patterns, **b** 3D infill patterns, and **c** various infill density for tri-hexagon/stars pattern

7.9 Infill Density

Infill density is defined as the percentage of infill volume with filament material. It can range from 0% (completely hollow) to 100% (completely solid). Higher infill density means that there is more material, hence higher strength and weight of part. Comparison of different infill density are depicted in Fig. 10c.

7.10 Air Gap

Air gap is referred to the gap between two adjacent beads on a deposited layer. In slicer software generally three kinds of air gap can be specified in a layer, which includes gap between two adjacent perimeter; gap between two adjacent interior raster; and gap between innermost perimeter and outermost interior raster. The value of air gap can be either positive, zero or negative, as depicted in Fig. 11. In case of zero air gap, the two adjacent raster just touch. A positive air gap means that two adjacent raster do not touch, which creates less dense structure having faster build time. Negative air gap means that two adjacent raster overlap on each other, which creates relatively dense structure with higher build time. Generally negative air gap is preferred to improve mechanical properties [11].

7.11 Print Speed

Print speed is referred to the travel speed of the printhead along the XY plane while extruding. Typical print speed for FDM printer varies from 30 to 80 mm/s.

Print speed affects the build time of printed part. With increase in the print speed, build time reduced. Low print speed is recommended to gain a higher print precision, as at higher speed dynamic effect of drive system increases, which give rise to jerky motion [13]. Speed is also constrained by maximum volumetric flow rate of extruder head. The maximum speed can be calculated by following Eq. (1) [15].

$$\text{Max. print speed} = \frac{\text{Max. volumetric flow rate}}{\text{Layer height} \times \text{Raster width}} \quad (1)$$

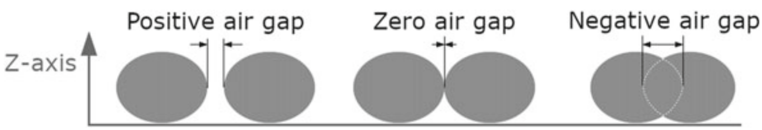

Fig. 11 A schematic representation of two adjacent raster cross-section, showing different airgap conditions

7.12 Build Volume Temperature

The build volume temperature can only be maintained when printer is with enclosures. Enclosures can improve printing performance by keeping dust and wind out and heat in. Not much research has been made to check effect of build volume temperature on FDM printed parts.

7.13 Build Platform Temperature

The build platform is generally heated to improve adhesion of first layer of the part to the build platform. The build platform temperature is recommended to kept slightly above the glass transition temperature of the filament material to achieve the optimal adhesion [20].

7.14 Skirt and Brim

Brim is referred to an extra area outside part boundary, attached to extreme edges of part in a first layer, as depicted in Fig. 12a. It is provided to increase surface area for the better adhesion of printed part to the build platform. It also reduces warping. Once the print it is finished, brim is cut away.

The skirt is a printed outline at a short distance away from the perimeter of the object, as depicted in Fig. 12b. The skirt is deposited on the build platform before starting to print the part in order to ensure that the material is flowing smoothly from the printhead.

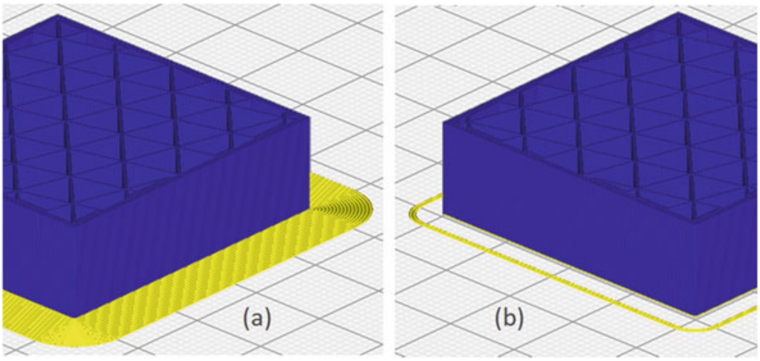

Fig. 12 FDM printed part (blue) with **a** Brim (yellow) and **b** skirt (yellow)

7.15 Processing Parameter Correlations

Processing-structure-property relationships in FDM are complex, nonlinear and poorly understood [21]. Understanding of this correlation having key significance to lead a way for standardizing the process and maximizing adaptation by industry [12]. Various process parameters influence the build time, mechanical characteristics, surface quality and dimensional accuracy of printed part in indirect or direct manner. Nevertheless, not all process parameters have same impact on various outcome, some process parameters have strong effect while other have smaller impact. Researchers focusing on some key parameters, which are illustrated with aid of ishikawa diagram as depicted in Fig. 13.

Due to unavailability of standards for FDM machine, materials and test procedures, benchmarking of results obtained from a variety of research studies focused on process parameters is complex task. In other words, for current research status, generalizing the results obtained from various research is almost impossible due to complex correlations among process parameters [11]. Although, few common takeaways confirmed by majority of studies are listed below.

- Extrusion temperature, build platform temperature, build volume temperature, infill pattern, perimeters, perimeter wall width and nozzle diameter are currently insufficiently studied in the literature [11, 13].
- Layer thickness, build orientation, raster angle, infill pattern, infill density and air gap are the key parameters having significant effect on mechanical properties of FDM printed parts [11, 21, 22].
- Tensile strength is increased with rise in infill density and perimeters [14].
- Tensile strength is maximum when the direction of extruded raster of part are parallel to the direction of the applied force [11, 23–26]. This can be achieved by proper combination of build orientation and raster angle.
- Build time is found minimum at higher layer thickness, low infill density, zero raster angle and build orientation having minimum support structure [13].

Further research is needed to investigate combined effect of process parameters on compressive strength, flexural strength and fatigue strength.

8 Defects in FDM Printed Parts

There are few common defects associated with FDM (as depicted in Fig. 14) due to variety of reasons, including and not limited to poor calibration of printer, selection of wrong operation parameters etc.

Warping is most usual quality issue in FDM printed parts. In warping, generally base of the printing part is bent upwards due to thermal contraction of the upper layers. This occurs due to variation in cooling rates between different layers of the print. It can be prevented by increasing the adhesion between the part and the build

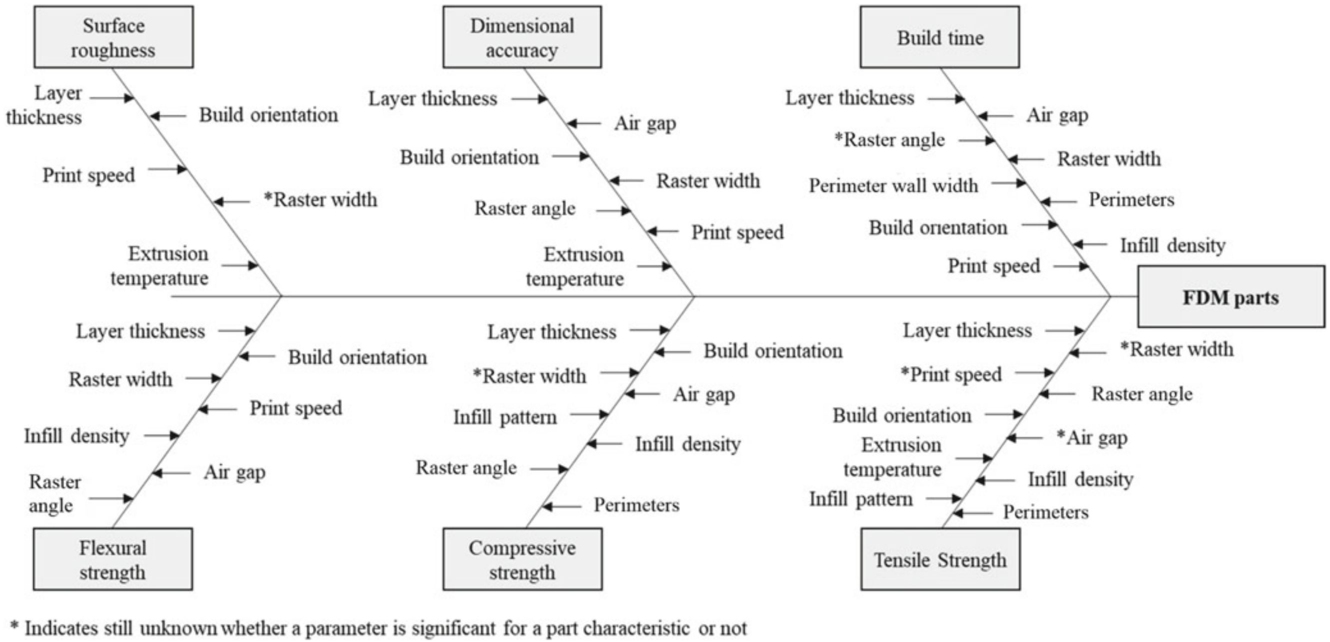

Fig. 13 An Ishikawa diagram to illustrate the effects of FDM process parameters on part characteristic (Image permission under the Creative Commons Attribution License 4.0, adapted from [13])

platform, and maintaining proper temperature of the FDM system. Another similar defect, called elephant's foot, occurred on base layers of part where material build-up occurs in the X-Y plane. It occurs when the nozzle is very close to the build platform or the temperature of the build platform is very high.

Layer shifting or layer misalignment is a displacement of print layers at a certain height from their intended positions in the X-Y plane. FDM printers with an open-loop control system, generally have this problem. The printer cannot detect wrong position of printhead if for any reason a servo motor loses steps, and print will continue with a wrong position.

Stringing or oozing is hairy strings of plastic that sometimes occurs in open area between two sections of print. Stringing happens when a small amount of plastic leaks and drips out of the nozzle, leaving a small thread stick to two sections in open area. This problem is usually caused by inaccurate settings used during the slicing process. It can be prevented by reducing extrusion temperature and proper filament retraction setting.

Ringing is a wavy pattern that may appear on the surface of printed part. It occurs due to printer vibrations, which are usually caused by the inertia of the printhead and when there are sudden direction changes. Reduction in the printing speed will reduce the ringing. Mechanical vibrations due to loosen and damaged machine components should be fixed to reduce the ringing.

Z-wobble is usually spotted when the printed layers are not perfectly aligned laterally with their adjacent layers above and below. Z-wobble may appear to look like ridges or lines appear in a repeating pattern on the sides of part. This problem is may be due to mechanical issues, temperature fluctuations or poor filament quality.

Curling or overheating occurs due to melting material at a very hot temperature, that will cause deformation in the part having curled corners and sagged layers. This

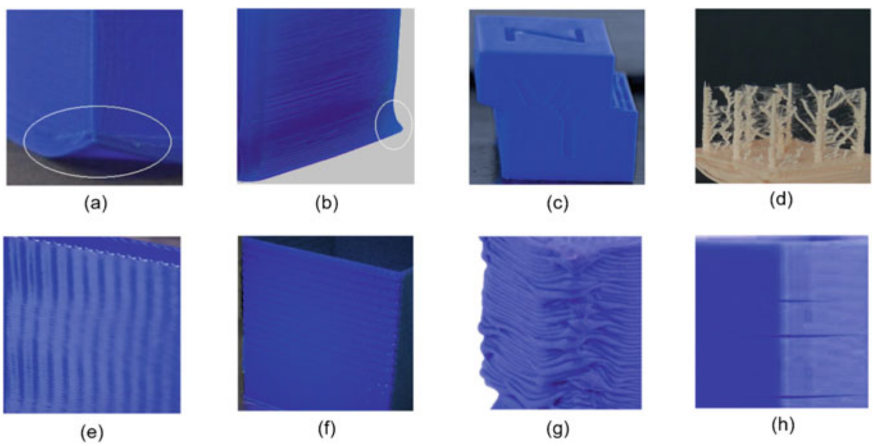

Fig. 14 Defects in FDM printed parts, **a** warping, **b** elephant's foot, **c** layer shifting, **d** stringing, **e** ringing, **f** z-wobble, **g** curling, and **h** layer separation

occurs as high temperature melt does not solidify and retain its shape in time, which cause layers to collapse or sag. This problem can be simply resolved by reducing printing temperature and increasing cooling.

Layer separation occurs when the layers of a part do not bond, resulting in these layers being separated. This defect occurs due to poor bonding between the layers. This can be resolved by increasing the print temperature or reducing the layer fan speed.

9 Advantages and Limitations

The advantages associated with FDM are as listed below.

- Compare to other major 3D printing methods, FDM is more affordable, accessible and cost-effective. Due to these reasons it is most used 3DP technology and best suited for beginners.
- FDM printer is relatively simple to operate and maintain.
- The process is relatively clean, safe and doesn't require the use of harsh chemicals.
- Feedstock materials are very diverse, readily available and affordable.
- Broad range of thermoplastic materials and exotic filaments can be printed with no or relatively few alterations on any FDM printer.
- Design of FDM printer can be scaled easily compare to other 3DP technology. They are available in size that can fit on a desktop to size of large wardrobe.

The limitations associated with FDM are as listed below.

- The major limitation of FDM is part strength and anisotropy. Parts build by FDM are not fully dense and z-axis anisotropy arises as inter-layer bonding is not as strong as intra-layer bonding.
- Surface quality (including volumetric error, shape deviation and surface finish) of FDM is not as good as other major 3D printing methods.
- High detail prints are hard to achieve.
- Unsuitable for thin-walled products. As per thumb rule, recommended minimum wall thickness for horizontal/vertical wall is 1 mm, while curved and slant wall will require more thickness.
- FDM is primarily limited to thermoplastics based pure- and composite- materials. Metal and ceramic material printing is possible by using thermoplastics-based metal/ceramic reinforced filament, but it requires secondary sintering operation and resultant part will not be fully dense.

References

1. ISO/TC 261 (2015) ISO/ASTM 52900:2015. Additive manufacturing—general principles—Part 1: terminology
2. Carew RM, Errickson D (2020) An overview of 3D printing in forensic science: the tangible third-dimension. J Forensic Sci 65:1752–1760. https://doi.org/10.1111/1556-4029.14442
3. RepRap (2019) (2020) Fused filament fabrication—RepRap. In: Reprap.org. https://reprap.org/wiki/Fused_filament_fabrication. Accessed 16 Nov 2020
4. Masood SH (2014) Advances in fused deposition modeling. In: Advances in additive manufacturing and tooling. Comprehensive materials processing, vol 10, pp 69–91. Elsevier
5. Mwema FM, Akinlabi ET (2020) Basics of fused deposition modelling (FDM). In: fused deposition modeling, pp 1–15. Springer
6. Varotsis AB (2020) Introduction to FDM 3D printing| 3D Hubs. In: 3D Hubs. https://www.3dhubs.com/knowledge-base/introduction-fdm-3d-printing/. Accessed 16 Nov 2020
7. Moreau C (2020) The state of 3D printing. https://www.sculpteo.com/blog/2020/06/02/download-our-state-of-3d-printing-2020-for-free/. Accessed 16 Nov 2020
8. Qin Y, Qi Q, Scott PJ, Jiang X (2019) Status, comparison, and future of the representations of additive manufacturing data. Comput Aided Des 111:44–64. https://doi.org/10.1016/j.cad.2019.02.004
9. Kumar S (2020) Other solid deposition processes. Additive manufacturing processes. Springer, Cham, pp 111–130
10. Elkaseer A, Schneider S, Scholz SG (2020) Experiment-based process modeling and optimization for high-quality and resource-efficient FFF 3D printing. Appl Sci 10:2899. https://doi.org/10.3390/app10082899
11. Popescu D, Zapciu A, Amza C et al (2018) FDM process parameters influence over the mechanical properties of polymer specimens: a review. Polym Testing 69:157–166. https://doi.org/10.1016/j.polymertesting.2018.05.020
12. Dizon JRC, Espera AH Jr, Chen Q, Advincula RC (2018) Mechanical characterization of 3D-printed polymers. Addit Manuf 20:44–67. https://doi.org/10.1016/j.addma.2017.12.002
13. Dey A, Yodo N (2019) A systematic survey of FDM process parameter optimization and their influence on part characteristics. J Manuf Mater Process 3:64. https://doi.org/10.3390/jmmp3030064
14. Turner BN, Strong R, Gold SA (2014) A review of melt extrusion additive manufacturing processes: I. Process design and modeling. Rapid Prototyp J 20:192–204. https://doi.org/10.1108/rpj-01-2013-0012
15. Gibson I, Rosen D, Stucker B (2015) Extrusion-based systems. Additive manufacturing technologies. Springer, New York, pp 147–173
16. Jiang J, Xu X, Stringer J (2018) Support structures for additive manufacturing: a review. J Manuf Mater Process 2:64. https://doi.org/10.3390/jmmp2040064
17. Das P, Mhapsekar K, Chowdhury S et al (2017) Selection of build orientation for optimal support structures and minimum part errors in additive manufacturing. Computer-Aided Des Appl 14:1–13. https://doi.org/10.1080/16864360.2017.1308074
18. Di Angelo L, Di Stefano P, Guardiani E (2020) Search for the optimal build direction in additive manufacturing technologies: a review. J Manuf Mater Process 4:71. https://doi.org/10.3390/jmmp4030071
19. Bikas H, Lianos AK, Stavropoulos P (2019) A design framework for additive manufacturing. Int J Adv Manuf Technol 103:3769–3783. https://doi.org/10.1007/s00170-019-03627-z
20. Spoerk M, Gonzalez-Gutierrez J, Sapkota J, Schuschnigg S, Holzer C (2017) Effect of the printing bed temperature on the adhesion of parts produced by fused filament fabrication. Plast, Rubber Compos 47:17–24. https://doi.org/10.1080/14658011.2017.1399531
21. Braconnier DJ, Jensen RE, Peterson AM (2020) Processing parameter correlations in material extrusion additive manufacturing. Addit Manuf 31:100924. https://doi.org/10.1016/j.addma.2019.100924