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Review of Printing Parameters on Mechanical Properties in FDM 3D Printing Process

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Abstract

Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) is a material extrusion process that commonly uses additive manufacturing. FDM uses thermoplastic polymers as filament stored in a reservoir or container. The filament is extruded from the print nozzle by application of pressure at specific temperatures. The object to be printed is governed by various material and machine parameters. The material to be printed is continuously extruded through the extruder nozzle of the printer through two rollers moving in opposite directions. The filament extruded on the built platform is stacked layer-by-layer until the formation of the object. The printing takes place as CAD model from the software is sliced, which acts as an input to the 3D printer, causing the print nozzle to move in desired arrangements and paths based on the G-Codes obtained from the slicer software. Few machines also possess dual extrusion or two extruders providing printing of different materials based on the needed properties of the product. The liquefaction or melting of the filament at temperatures varies with the materials to be extruded. The properties of the manufactured parts depend on the material used and its parameters, such as mechanical and thermal properties. Layer resolution, build orientation, temperature, raster angle, and air gap, known as the machine parameters, play the decisive role for a good printed FDM part.

Keywords
3D Printing, Raster Angle, Layer Thickness

1. Introduction

Fused deposition modeling (FDM) is one of the methods used in 3D printing. This technique is one of the manufacturing methods under the additive manufacturing engineering class, gaining popularity among researchers and industry to study and develop. Additive manufacturing techniques can create various complex shapes and structures while properly managing materials, resulting in less waste and various other advantages over conventional manufacturing, making it increasingly popular. Technically, the FDM technique has the same role as injection molding in the manufacturing aspect. For example, mass customization. It means producing a series of personalized items, so that each product can be different while maintaining low prices due to mass production.

The basic concept of the FDM manufacturing process is simply melting the raw material and forming it to build new shapes. The material is a filament placed in a roll, pulled by a drive wheel, and then put into a temperature-controlled nozzle head and heated to semi liquid. The nozzle precisely extrudes and guides materials in an ultrathin layer after layer to produce layer-by- layer structural elements. This follows the contours of the layer specified by the program, usually CAD, which has been inserted into the FDM work system.

Since the shapes in FDM are built from layers of the thin filament, the filament thermo plasticity plays vital role in this process, which determines the filament's ability to create bonding between layers during the printing process and then solidify at room temperature after printing. The thickness of the layers, the width, and the filament orientation are the few processing parameters that affect the mechanical properties of the printed part. The complex requirements of FDM have made the material development for the filament a quite challenging task.

Research on this material stigmatizes the limitations of the material for this technique. Currently, 51% of the products produced by the additive manufacturing system are polymer–plastic filament types. It is because these materials not only have sufficient criteria to be used and developed but also help to make FDM processes for manufacturing products more manageable and more optimal. The most well- known polymers used in this technique are poly lactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Moreover, other materials such as polypropylene (PP) also began to be noticed for development because it is one of the plastics that is commonly found in everyday life. In Japan filaments made of PP are being used and offer superior resistance to heat, fatigue, chemicals, and better mechanical properties such as stiffness, hinges, and high tensile strength with a smooth surface finish. Also, several other types of filaments are currently being developed and introduced as commercial filaments.

Some previous studies showed that although the filament composition is the same, the test may obtain different results. In other studies, some researchers optimized the performance of FDM machine by changing some of the parameters and concluded that each combination of parameters would be showing different results. These studies have shown that many factors critically determine the results of the FDM process (Figure 1).

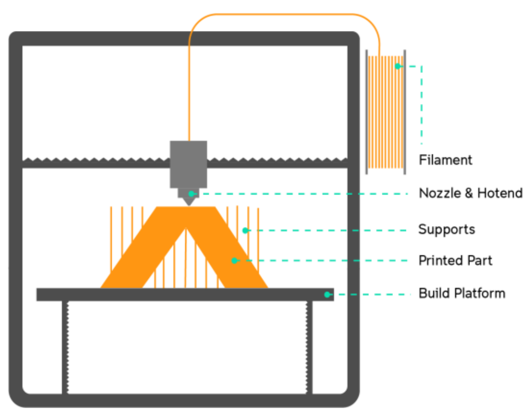

Figure 1: FDM printer parts

This study aims to provide a comprehensive picture of the various factors that influence the mechanical characteristics of FDM products. The review is carried out by critical mapping parameters and critical parameters determining FDM factors and analyzing each parameter's main effects and their interactions in the FDM process.

The review starts with producing the filaments, the impact of different filament materials, and the critical printing parameters of the FDM techniques. Understanding these factors will be useful to get a combination of each influential factor, which can later be optimized to obtain printing results with mechanical properties that can be adjusted to the target application.. FDM is the easiest 3d printing method. Besides, the printer is smaller, the process is safer, and uses cheaper materials. Therefore it has an edge over other 3d printing methods and will continue to develop in the future at a great pace.

Printing process on the FDM machine

The FDM machine's working principle is to heat the filament on the nozzle to reach a semi liquid state and then extruding it on a plate or layer that was previously printed. Thermo plasticity of polymer filaments allows the filaments to fuse during printing and then solidify at room temperature after printing. Although a simple 3D printing using the FDM method has complex processes with various parameters that affect product quality and material properties, each of these parameters is linked to one another, making this combination of parameters often challenging to understand In contrast, every product that results from the 3D printing process has different quality requirements and material properties. The print parameter combination on the FDM machine is determined by the type of filament and the size of the filament used in the FDM process. Therefore, it is crucial to examine the effect of a combination of mechanical performance parameters. The parameters that affect the printing process are divided into two categories, namely, the parameters of the FDM machine and the working parameters. Machine parameters include bed temperature, nozzle temperature, and nozzle diameter. In contrast, the working parameters include raster angle, raster width, build orientations, etc., and these parameters are usually inputted in the slicing process using the software before the design and work parameters are entered into the FDM machine (Figure 2).

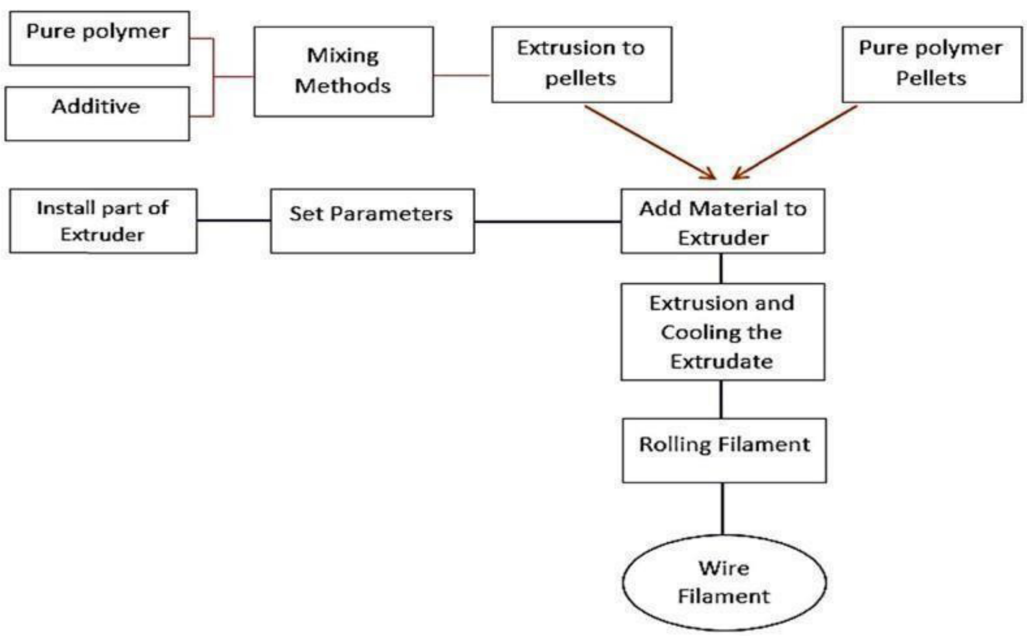

Figure 2. Printing process

The following explains some of the main parameters of the FDM printing process. explains the build orientation guided by the step where the part is oriented toward the *X*, *Y*, and *Z* axes on the build platform. Layer thickness is the thickness of the layer deposited on the nozzle tip. The user's thickness value in a specific range is defined by the nozzle diameter and limited by the printer accuracy. Some studies suggest using a thinner layer to increase both the surface quality and accuracy (Figure 3).

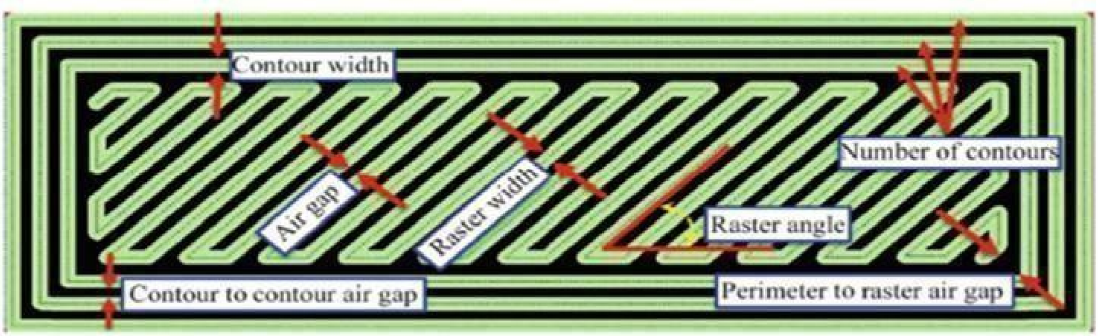

Figure 3. FDM Tool path parameters

1.1. Objectives

- Identify and understand the main FDM printing parameters such as layer height, infill density, printing speed, nozzle temperature, print orientation, and build plate temperature.
- Investigate how variations in these printing parameters affect mechanical properties like tensile strength, flexural strength, impact resistance, and surface finish.
- Develop strategies to optimize printing parameters to achieve the best possible mechanical properties for different materials and applications.
- Study the interaction between specific materials (such as PLA, ABS, PETG, etc.) and printing parameters to assess how different materials respond to changes in the printing environment.
- Assess the balance between mechanical properties, print time, and material consumption, and recommend settings that optimize both performance and efficiency.

2. Literature Review

We conducted literature review on various printing parameters in FDM 3D Printing process such as Build orientation, Printing speed, Layer thickness, Extrusion temperature, Infill density, Raster angle and Infill patterns.

2.1 Build Orientation

Nicholas Beattie et al. (2021) stated the strong correlation between build orientation and mechanical properties of fused deposition modeling parts. The tension experiment found that the tensile modulus with the greatest value was produced using the edgewise build orientation. The best print orientation for maximum tensile strength was also produced with an edge up build orientation. Vertically printed parts showed significantly lower UTS and elongation at break in tension. In bending, edgewise also showed the highest flexural modulus and elongation at break while vertically oriented parts were substantially weaker in modulus. In bending, edgewise also showed the highest flexural modulus and elongation at break while vertically oriented parts were substantially weaker in modulus, UFS and elongation at break. For torsion, all print orientations had similar moduli and USS, but significantly different angle at break with horizontally oriented parts being best, and angle oriented parts faring the worst. Jochen Mueller Kristina Shea. et al. (2018). The highest strength and failure strains are reached at the in- plane orientations. Any involvement of Z quickly reduces the strength and fracture strains, and the lowest values for these properties are found when the parts are aligned along Z (Figure 4).

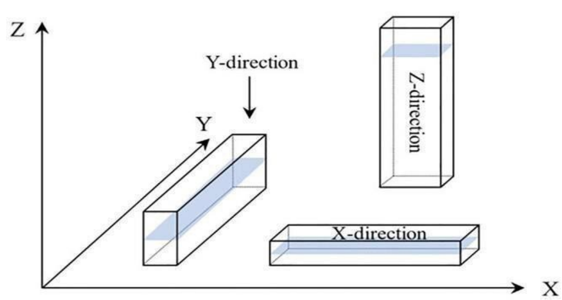

Figure 4. Graphical representation of Build orientation

Jayant Giri et al. (2021) stated that for the horizontal orientation, as the layer thickness increases from 0.05 to 0.1 mm, tensile strength increases but as the layer thickness increases above 0.2 mm tensile strength decreases. But there is no significant effect of cooling rate on tensile strength. For vertical orientation, maximum tensile strength is obtained for the sample with a layer thickness of 0.2 mm. But the further increase in layer thickness causes decrease in the tensile strength.

2.2 Printing speed

K.G. Jaya Christiyan et al. (2016) A low printing speed with low layer thickness gives a better bonding with the previous layer due to that it exhibited a better tensile and flexural strength. tensile stress decreases with increase in printing speed. Anis A. Ansari et al. (2021). A higher tensile strength was found at print speed of 50 mm/s, whereas a lower tensile strength was observed at the print speed of 40 mm/s. In other words, higher tensile strength is obtained at a high level of print speed. A higher tensile strength noted at the higher print speed is due to the quick bonding between the successive layer interfaces. Minimum build time is achieved at a higher print speed as it inversely depends upon the print speed. Mohammad Reza Khosravani et al. (2020) stated that the printing speed and raster direction, the latter showed greater effects on the strength of 3D-printed components.

2.3 Layer thickness

K.J. Jaya Christiyan et al. (2016) that tensile and flexural strength part is made with thicker layer then each individual layer shows more resistance against the failure as compared to part of same thickness made with thinner layer. Tensile and flexural strength of the material is decreasing with respect to increasing layer thickness, this is due to the stepped effect, in this layer deposited over another layer is due the sample orientation. Jayant Giri et al. (2021) stated that the layer thickness increases the printing time gradually decreases. So, we can conclude that printing time has an inversely proportional relation with layer thickness. With the increase in the layer thickness (in mm), higher produce faster prints with low tenacity and lower values produce slower prints with greater tenacity. M. Samykano et al. (2019), It was found that the optimum parameters for 3D printing using ABS is0.5mm layer thickness (Figure 5).

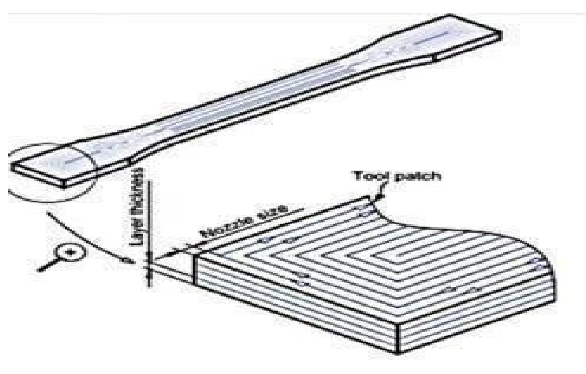

Figure 5. Layer thickness

Shuheng Wang et al. (2020) that the storage modulus, loss modulus, and loss factor of the FDM-printed PLA materials decrease with increasing layer thickness. Yanping Liu et al. (2021) stated that increase in layer thickness resulted in a decrease in the strength of a tray and an increase in time efficiency but had little effect on the dimensional accuracy. Ei Ei Cho, Ho Hin Hein et al. (2019) stated that Layer thickness have higher influence than infill pattern on mechanical properties, The higher the layer thickness the higher the mechanical strength.

2.4 Extrusion Temperature

Anis A. Ansari et al. (2021) stated that higher extrusion temperature helps in a better layer to layer fusion which further improves the part strength ,extrusion temperature has no effect on build time that the air gap between raster increases with increase in the extrusion temperature. The maximum air gap is observed at

temperature 230 _C. It is also evident that the raster width is higher at lower extrusion temperature and it significantly decreases with the increase in the extrusion temperature.
Shuheng Wang et al.stated that When the nozzle temperature is raised from 210 C to 230 C, the elastic modulus and tensile strength of the material decrease slightly, and the elongation at break decreases rapidly.

2.5 Infill Density

M. Samykano et al. (2019) the maximum UTS which could be achieved is 33.187 MPa and it is achievable with of 80% infill density, It was found that the optimum parameters for 3D printing using ABS are 80% infill percentage. Shuheng Wang et al. 2021) stated that the increase of the fill rate, the air gaps in the material decrease rapidly, which makes the material layers and the filaments more tightly bonded, and the PLA molecular segment movement resistance increases. This not only increases the storage modulus of the printed material, but also increases its loss modulus and loss factor. Md. Qamar Tanveer et al. (2019) the impact strength increases if the inner layer is of higher infill density and outer shell are of lesser density, varying infill density exhibit better tensile strength than the specimens with single infill density. The varying infill density specimens weigh lighter as compared to single infill density, which saves the raw material. The dense infill exhibits higher resistance to break, but the less dense infill shows greater flexibility, which helps to increase the peak displacement.

2.6 Raster Angle

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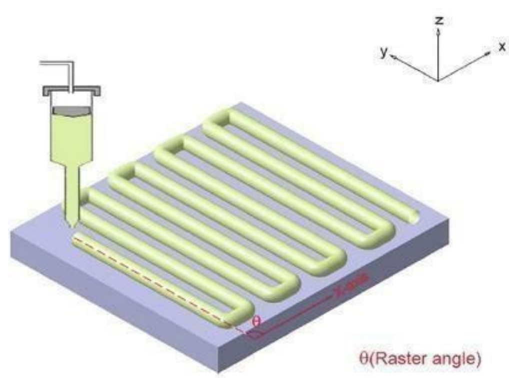

Figure 6. Raster angle

Shuheng Wang et al. (2020) stated that Fill rate determines the effective cross-sectional area in the tensile direction and interlayer bonding strength of the FDM-printed materials. Ei Ei Cho, Ho Hin Hein et al. (2019) stated that Layer thickness have higher influence than infill pattern on mechanical properties. Mohammadreza Lalegani Dezaki et al. (2020) stated that the patterns are situated layer by layer properly. The quality of the printed pattern at 0_ angle was good and showed the FDM process is capable to combine patterns but these patterns must be designed in CAD software separately due to the system limitations to combine patterns. developing a new algorithm to combine patterns in different layers in the slicing process helps to conduct products with higher strength

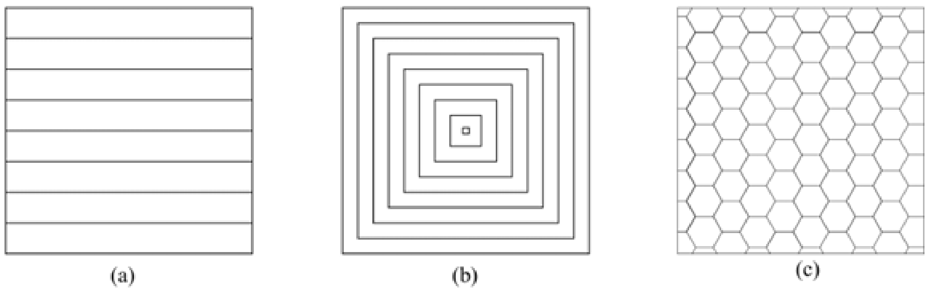

Figure 7. Infill patterns a) Linear b) Concentric c) Hexagon

and stiffness. Combining various patterns can be used in different applications to achieve stronger products without sacrificing properties. DUDESCU Cristian et al. (2017) stated that Infill pattern influence has been studied for printed specimens with 100% infill and rectilinear 0° and 90°, grid 0°-90° and 45°-45°, fast honeycomb, full honeycomb, triangular (60°) and wiggle patterns (Figure 7).

3. Methods

3.1 Selective Laser Sintering

Selective laser sintering (SLS) was developed and patented by Dr. Carl Deckard and academic adviser, Dr. Joe Beaman at the University of Texas in the mid-1980, under the sponsorship of DARPA.[2] Deckard was involved in the resulting start-up company DTM, established to design and build the selective laser sintering machines. In the year 2001, 3D Systems the biggest competitor of DTM acquired DTM. The most recent patent regarding Deckard's selective laser sintering technology was issued on January 1997 and expired on Jan 2014. Selective laser sintering is a 3D-printing technique that uses a laser as the power source to sinter powdered material (mostly metal), aiming the laser at points in space defined by a 3D model, binding the material to create a solid structure. Selective laser melting uses a comparable concept, but in SLM the material is fully melted than sintered, allowing different properties (crystal structure, porosity). SLS is a relatively new technology that so far has mainly been used for additive manufacturing and for low-volume production of parts. Production roles are expanding as the commercialization of additive manufacturing technology improves.

3.2 Fused Deposition Modeling

Fused deposition modeling (FDM) method was developed by S. Scott Crump in the late 1980s and was designed in 1990 by Stratasys. After the patent on this technology expired, a large open source development community developed and commercial variants utilizing this type of 3D printer appeared. As a result, the price of FDM technology has dropped by two orders of magnitude since its creation. In this technique, the model is produced by extruding small beads of material which harden to form layers. A thermoplastic filament or wire that is wound into a coil is unwinding to supply material to an extrusion nozzle head. The nozzle head heats the material up to the certain temperature and turns the flow on and off. Typically the stepper motors are employed to move the extrusion head in the z-direction and adjust the flow according to the requirements. The head can be moved in both horizontal and vertical directions, and control of the mechanism is done by a computer-aided manufacturing (CAM) software package running on a microcontroller.

3.3 Stereolithography

Stereo lithography is an early and widely used 3D printing technology. 3D printing was invented with the intent of allowing engineers to create prototypes of their own designs in a more time and in an effective manner. The technology first appeared as early as 1970. Dr. Hideo Kodama Japanese researcher first invented the modern layered approach to stereo lithography by using UV light to cure photosensitive polymers. On July 1984, before Chuck Hull filed his own patent and Alain Le Mehaute filed a patent for the stereo lithography process. The French inventor's patent application was neglected by the French General Electric Company and by CILAS (The Laser Consortium). Le Mehaute believes that abandonment reflects a problem with innovation in France. Stereo lithography is a form of 3-D printing technology used for creating models, prototypes, patterns in a layer by layer fashion using photo polymerization, a process by which light causes chains of molecules to link together, forming polymers. Those polymers then make up the body of a three-dimensional solid. Research in the area had been conducted during the 1970s, but the term was coined by Charles (Chuck) W. Hull in 1986 when he patented the process. He then set up 3D Systems Inc. to commercialize his patent.

3.4 Laminated Object Manufacturing

It is a 3D-printing technology developed by Helisys Inc. (now Cubic Technologies). In it, layers of adhesive-coated paper, plastic, or metal laminates are successively joined together and cut to appropriate shape with a laser cutter. Objects printed with this technique may be additionally modified by machining after the printing process. the typical layer resolution for this process is defined by material feedstock and usually ranges in thickness from one to a many sheets of paper of a copy.

4. Data Collection

4.1 Filament manufacturing:

The filament is the primary material used in the FDM process. In general, the filament is made of pure polymer with a low melting point. In some cases, the strength of pure polymer needs to be enhanced. Therefore, many researchers and industries have developed polymer composites as 3D printing filament material by combining the matrix and enhancing the components to achieve systems with structural properties and functional benefits which cannot be achieved by just any constituent .The filaments made from pure polymers that are usually commercial can be directly processed as FDM material. However, the process of making composite filaments must first receive special treatment because every reinforcement in a composite polymer will result in different characteristics. The pure polymer filament for FDM materials can be made through the process of extruding pellets or raw materials from polymers. This process is carried out using extruders that push or force the material through holes in the die to get the product as an extrudate. Meanwhile, making filament from polymer composites or by strengthening is accomplished by mixing the material before the extrusion process is carried out by preparing each composition in advance so it can be associated .The materials can be mixed by several methods depending on the characteristics of the ingredients of the mixture. It can be completed by mixing the solution and then drying before being extracted or by the dry mixing method. This method is most often used for mixing polymer filament material using a pure polymer stirred in a stirring machine with spinning roller blades at a melting point temperature of the polymer. Then after the compatibilizer process, additives are added in stages according to the required percentage. It usually takes about 30min. After that the melted material is then allowed to stand at room temperature to achieve homogeneity.

The resultant mixture can be processed into pellets or pieces of fabric of small sizes ranging 4 ×4mm, and then it is processed in an extruder. In this extrusion process, several things affect the filament. Die temperature, roller puller speed, spindle speed, and inlet temperature affect the filament cable diameter. Because in this process, the parameters will affect the viscosity of the material, which causes the output of the material to be extruded at the nozzle die, not according to the desired diameter. In contrast, the winding screw shape affects the regularity of the filament. Especially in composite filaments, the shape of the thread will affect the direction of the filler used in the filament.

4.2 Materials used in FDM 3D Printing

The most common FDM 3D printing materials are ABS, PLA, and their various blends. More advanced FDM printers can also print with other specialized materials that offer properties like higher heat resistance, impact resistance, chemical resistance and rigidity. FDM filaments are also relatively low cost compared to materials for other 3D printing technologies (Table 1). Common FDM materials like ABS, PLA, and their various blends generally start around $50/kg, while specialized FDM filaments for engineering applications can be $100-150/kg. Soluble support materials for dual extrusion FDM 3D printers sell for $100-200/Kg (Figure 8).

Figure 8. Filament

Table 1. Materials used in FDM printers

MATERIAL	FEATURES	APPLICATIONS	Limitations
ABS (acrylonitrile butadiene styrene)	Tough and durable, Heat and impact resistant, Requires a heated bed to print, Requires ventilation	Functional prototypes	Warping, Odor, Temperature
PLA (polylactic acid)	The easiest FDM material to print, Rigid, Strong, but Brittle less resistant to heat and chemicals, Biodegradable, Odorless.	Concept models Looks-like prototype	Brittle, Dimensional Instability, oozing
PETG(polyethylene terephthalate glycol)	Compatible with lower printing temperatures for faster production Humidity and chemical resistant High transparency Can be food safe	Waterproof applications Snap-fit components	Stringing, Fusing to print bed, Painting or gluing
Nylon	Strong, durable, and lightweight Tough and partially flexible Heat and impact resistant Very complex to print on FDM	Functional prototypes Wear resistant parts	Less Strength, Consistency ,Complex
TPU (thermoplastic polyurethane)	Flexible and stretchable impact resistant, Excellent vibration dampening	Flexible prototypes	Less Print quality, Should be printed at low speed
PVA (polyvinyl alcohol)	Soluble support material, Dissolves in water	Support material	Clogging, Expensive, Short life
HIPS (high impact polystyrene	Soluble support material most commonly used with ABS Dissolves in chemical limonene	Support material	No Safety, Not UV resistant, low resolution
Composites (carbon fiber, kevlar, fiberglass)	Rigid, strong, or extremely tough Compatibility limited to some expensive industrial FDM 3D printers	Functional prototypes Jigs, fixtures, and tooling	Low fiber content, Brittle fracture

5. Results and Discussion

Fused Deposition Modeling (FDM) stands out as a favorable 3D printing option due to its low cost, ease of operation, and compatibility with a wide variety of thermoplastic materials. While it may have relatively long print times and lower resolution compared to other methods, its accessibility and versatility make it an ideal choice for many applications, especially for hobbyists and small-scale production. In contrast, methods like Selective Laser Sintering and Stereo lithography, while offering high-quality prints and large build volumes, tend to be more expensive and complex to operate. Laminated Object Manufacturing presents some advantages in terms of cost and large part production but faces challenges with material waste and design complexity. Overall, FDM remains a practical and user-friendly option in the 3D printing landscape (Table 2).

Table 2. Properties

S. No.	Parameters	Fused Deposition Modeling	Selective laser sintering	Stereo lithography	Laminated Object Manufacturing
1	Advantages	Low cost, easy to operate, wide variety of usable thermoplastic materials	Very large build volumes can produce mechanical functional prints out off ceramics metals, excellent surface quality	Can be low cost, high resolution and good surface quality	Low cost No need of support structures No deformation The possibility of building large parts
2	Limitations	Relatively long print time low printer resolution	Expensive and difficult to purchase and operative	Relatively long print time and expensive industrial grade printers	Fabrication material is subtracted, Complex internal cavities are difficult to build Fire hazards
3	Operation Principle	Extrusion of melted filament	Laser sintering	UV Curing	Deposition of sheet material
4	Melt Temperature°C	173-178	165-192	165-192	120-175
5	Printing Speed (mm/sec)	500	60	720	75
6	Print Volume(mm)	(300x300x300)	(165x165x300)	(353x196x350)	(500x800x500)
7	Equipment Cost	Printers range from $2000 To $8000 and industrial systems are available from $15000	Printers range from $30000 To $60000 and industrial systems are available from $200000	Printers range from $2500 To $10000 and industrial systems are available from $25000	Printers range from $14995 To $20000 and industrial systems are available from $65000
8	Material Cost	$50-$150/kg for most standard filament	$100/kg for nylon	$100-$200/L for most standard and engineering resins	$30-$40/kg for standard material
9	Training	Minor training on buildup setup, machine operation	Moderate training on buildup setup, maintenance and machine operation	Plug and play, Minor training on build setup	Moderate training on buildup setup, maintenance and machine operation
10	Strength	Good	Good	Medium	Medium
11	Resolution(µm)	100-300	100-300	50-200	Medium
12	Roughness	Medium	Weak	Good	Medium
13	Overall accuracy	Accurate and reliable process	Not very accurate	Most accurate printing process	Slightly less dimensional accuracy
14	Finish Options	Standard finish	Standard finish	Excellent surface finish	Wood like characteristics

15	Bed Temperature ℃	90-110	120-150	20-30	70-120
16	Layer thickness (mm)	0.1-0.3	0.06-0.15	0.05-0.15	0.001-0.005

6. Conclusions

FDM 3D printing is still not, and probably in the near future will not become a technology capable of displacing traditional manufacturing techniques in mass applications. FDM technology, however, allows the obtaining of unique individual elements with satisfactory properties and, in the case of personal 3D printers, also an acceptable price. Problems with the quality of 3D printing stems mostly from changing of environmental conditions, the required high accuracy calibration of a printer (especially the build table leveling), that is a necessary condition for obtaining proper adhesion of the first layer to the table. In order to obtain correct, non-deformed prints from some materials (PLA), direct cooling of the printed item is also necessary. The Effect of FDM process parameters of layer thickness, volume infill and print speed of PLA material was first systematically investigated in this study and also tensile test was performed. The results indicated that the optimal combination of tensile strength is layer thickness of 0.2-0.25mm, volume infill of 50-75%, and print speed of 18-20mm/sec. From this set of combinations the optimum tensile strength is obtained as 20-25 MPa.

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