A review on different process parameters in FDM and their effects on various required outputs

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Abstract - FDM (Fused deposition modelling) is the manufacturing technique in which product is built layer by layer with help of 3D printers by deposition of heated material through a nozzle. It can produce complex shapes which are nearly impossible to build through conventional subtractive manufacturing processes, also it is more efficient, economical, cheap and can produce wide variety of products. On the other hand, it has several major limitations like limited options of material, dimensional accuracy and surface finishing, poor material strength, and slow rate of production. Numerous research studies are ongoing on study to enhance the usage of FDM in different operational environments. Multiple researchers concentrated on composite materials such as carbon fibre composite, glass fibre reinforced composite, metal composites, polymer composites, and ceramic composites. This paper aims to provide a comprehensive review of substantial progress has been made in developing a range of samples and optimization of printing parameters for FDM.

***Key Words*: Additive manufacturing, process parameters, fused deposition modelling, composite materials, tensile and flexural strength**

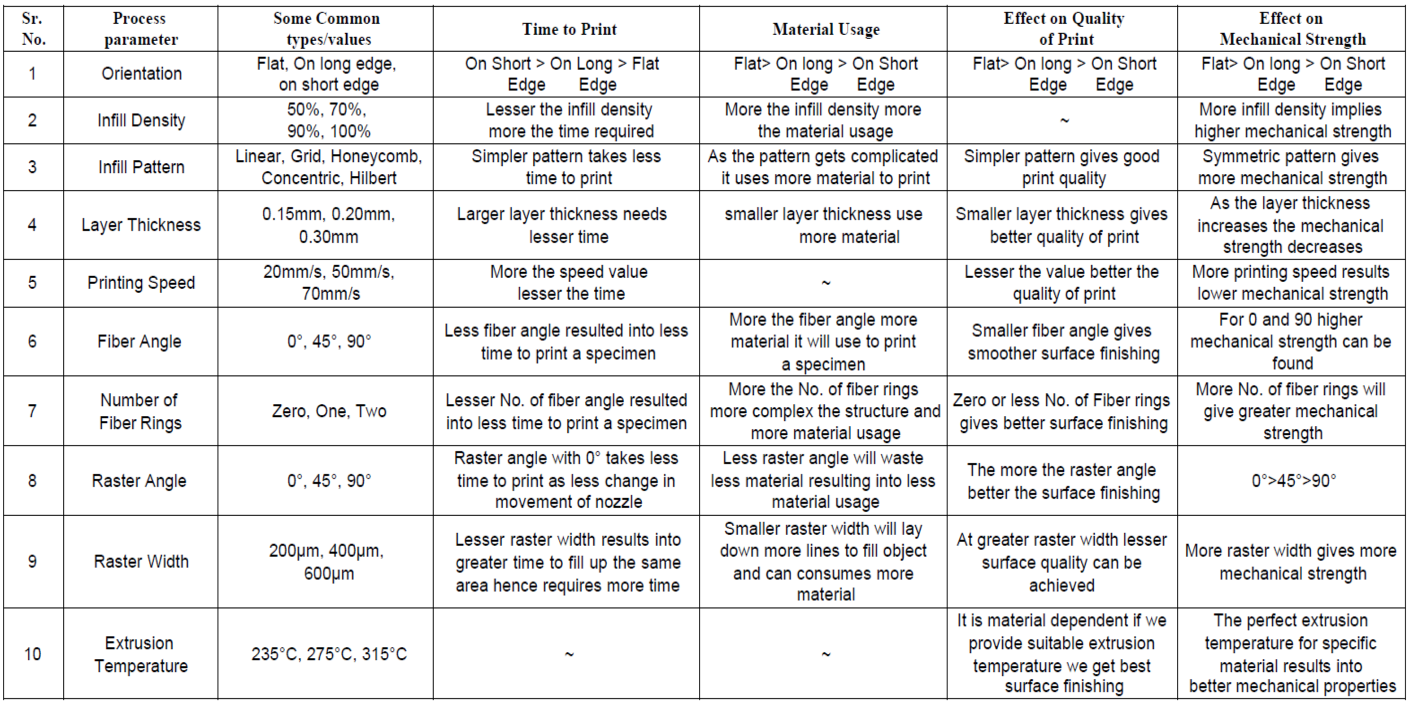
1. INTRODUCTION

The 3D Printing, a rapidly evolving additive manufacturing technology, has the potential to revolutionize the manufacturing industry by significantly reducing production time compared to traditional methods. With ongoing advancements, it is expected that 3D printers will soon dominate the market, replacing traditional manufacturing processes and initiating a new industrial revolution [1]. Additive manufacturing also known as 3D printing is one of the most revolutionary technology which permits the fabrication of the physical object by adding the material layer by layer to form a desired object which exactly similar to conventional subtractive manufacturing processes like laser cutting, CNC machining, milling machine cutting which ultimately facilitates the user with several benefits like Design freedom- 3D printing allows the tedious and intricate geometries which are very difficult or more likely impossible to accomplish with subtractive manufacturing. Material efficiency- the subtractive manufacturing process generates remarkable amount of material waste because of elimination of unwanted excess material, whereas additive manufacturing is very material effective because it consumes only required amount of material to generate an end product. Cost effectiveness of complex parts- conventional subtractive manufacturing process involves multiple steps, specialized tools and longer production time which eventually results in high costs of product but, the additive manufacturing can merge multiple components in the single printed object which also decreases assembly time as well as time. Customization- Additive manufacturing allows the generation of exclusive and personalized parts as per the individual requirements and preference. Reduced tooling costs- Additive manufacturing eliminates the requirements of specialized tools for custom parts or batch production as it is needed in conventional manufacturing method. Vishal N. Patel et al. conducted a review on the parametric optimization of the Fused Deposition Modelling process in rapid prototyping technology, focusing on different parameters such as layer thickness, air gap, raster width, raster orientation, and mechanical properties, and reviewing various studies that investigated the effects of these parameters on mechanical properties, surface roughness, build orientation, and quality of FDM parts [2] . The method for creating high-quality ABS wire as a feedstock filament for FDM is presented in this paper by examining the effects of extrusion parameters. This method produces ABS wire with favorable mechanical and thermal properties, printability, and bed adhesion, indicating its potential for industrial applications in the automotive, aerospace, and medical sectors [3].

2. Additive Manufacturing Process:

Additive manufacturing is the class of technology which automatically design the model using CAD data. *In recent years, additive manufacturing process has found various applications in many industrial as well as commercial sectors*. ABS and PLA are the most commonly used filaments in 3D printing both of them provide high quality materials in their own ways [4]. We can use various reinforcing materials to enhance the mechanical, thermal, and flame-retardant properties like glass fiber-reinforced modeling polymer (GFRP) using the fused deposition modeling (FDM) 3D printing process [5]. Leipeng Yang et al. investigated the impact of adding Carbon Nanotubes (CNT) to Polylactic Acid (PLA) in Fused Deposition Modelling (FDM), focusing on the enhancement of thermal, mechanical, and electrical properties, using two approaches: optimizing process parameters and utilizing new materials, resulting in improved mechanical properties, electrical conductivity, and thermal stability as CNT content increased in the PLA/CNT blend [6]. A table is formulated to correlate the various printing parameters and their effects on desired outputs. From this table, it can be understood that, none of those have similarities within them and they can be varied as per the requirements and availability of resources. FDM is the most popular among the different additive manufacturing processes such as stereo-lithography, fused deposition modeling, binder jetting, direct energy deposition and sheet lamination. R. B. Kristiwan et al. conducted a thorough review on FDM 3D printing, covering filament processing, materials, printing parameters, and their impact on product quality. They highlighted the need for printing parameter optimization to achieve improved mechanical properties and dimensional accuracy and discussed current issues and potential future research directions [7].

Table -1: Process parameters and their effects on required outputs



Sr. No.	Process parameter	Some Common types/values	Time to Print	Material Usage	Effect on Quality of Print	Effect on Mechanical Strength
1	Orientation	Flat, On long edge, on short edge	On Short > On Long > Flat Edge Edge	Flat> On long > On Short Edge Edge	Flat> On long > On Short Edge Edge	Flat> On long > On Short Edge Edge
2	Infill Density	50%, 70%, 90%, 100%	Lesser the infill density more the time required	More the infill density more the material usage	~	More infill density implies higher mechanical strength
3	Infill Pattern	Linear, Grid, Honeycomb, Concentric, Hilbert	Simpler pattern takes less time to print	As the pattern gets complicated it uses more material to print	Simpler pattern gives good print quality	Symmetric pattern gives more mechanical strength
4	Layer Thickness	0.15mm, 0.20mm, 0.30mm	Larger layer thickness needs lesser time	smaller layer thickness use more material	Smaller layer thickness gives better quality of print	As the layer thickness increases the mechanical strength decreases
5	Printing Speed	20mm/s, 50mm/s, 70mm/s	More the speed value lesser the time	~	Lesser the value better the quality of print	More printing speed results lower mechanical strength
6	Fiber Angle	0°, 45°, 90°	Less fiber angle resulted into less time to print a specimen	More the fiber angle more material it will use to print a specimen	Smaller fiber angle gives smoother surface finishing	For 0 and 90 higher mechanical strength can be found
7	Number of Fiber Rings	Zero, One, Two	Lesser No. of fiber angle resulted into less time to print a specimen	More the No. of fiber rings more complex the structure and more material usage	Zero or less No. of Fiber rings gives better surface finishing	More No. of fiber rings will give greater mechanical strength
8	Raster Angle	0°, 45°, 90°	Raster angle with 0° takes less time to print as less change in movement of nozzle	Less raster angle will waste less material resulting into less material usage	The more the raster angle better the surface finishing	0°>45°>90°
9	Raster Width	200µm, 400µm, 600µm	Lesser raster width results into greater time to fill up the same area hence requires more time	Smaller raster width will lay down more lines to fill object and can consumes more material	At greater raster width lesser surface quality can be achieved	More raster width gives more mechanical strength
10	Extrusion Temperature	235°C, 275°C, 315°C	~	~	It is material dependent if we provide suitable extrusion temperature we get best surface finishing	The perfect extrusion temperature for specific material results into better mechanical properties

FDM is the most commonly used additive manufacturing technique because it has several advantages over other techniques such as Accessibility and affordability of the 3D printers as compared to other additive manufacturing processes, it can be used with a variety of materials, this method is easy to use and even beginners can also make objects because of its friendly interface, and it has maximum flexibility by which one can control surface smoothness, mechanical and other strengths of the end product by varying its different printing parameters and their levels. Amir Rostami et al. demonstrated the influence of multiwalled carbon nanotubes (MWCNTs) on the rheological, thermal, and electrical properties of a PC/ABS blend, emphasizing the significant improvement in physical and mechanical properties achieved through the use of nanofillers, as well as the localization of MWCNTs at the interface of PC and ABS, which leads to increased electrical conductivity [8]. Dinesh Yadav et al. successfully used an artificial neural network to optimize the FDM 3D printing process parameters for multi-material printing, leading to better print quality and fewer defects. This work has potential ramifications for manufacturing processes that are more effective and economical [9].

3. Challenges in AM

Additive manufacturing is replacing the traditional manufacturing processes because of its advantages like design freedom, reduced tooling costs, product customization, sustainability, and waste reduction though AM has a hard path ahead to get accepted for real-time product application. Some of the important challenges faced by AM are limited size of part to be printed, misalignments in the top layers, cost of the production, material selection, less accuracy, cost of the production. Dinesh S.K. et al. studied the flexural and tensile behavior of PLA, ABS, and PLA-ABS materials in 3D printing, evaluating various printing parameters and proportions, and discovered that the sandwiching of ABS and PLA in 3D printed samples demonstrated promising mechanical properties, indicating its potential as a future filament option in additive manufacturing [4].

3.1. Post-processing and finishing:

It plays a very crucial role in AM to fulfill desired dimensional accuracy, surface finishing, and aesthetics of the printed parts. It increases the cost and time required to manufacture a specific product for end use. The printing of overhangs and complex geometries is facilitated by several AM techniques by use of support structures. This support must be taken down after printing, is can be carried out manually with the aid of cutting implements or chemical solvents, or automatically utilizing technique like water jetting or supports those dissolves. Because AM is an additive technique, parts frequently have layered surface textures. There are many methods that can be used, such as sanding, polishing, or abrasive blasting to enhance the surface finishing. These techniques help in reducing surface roughness and apparent layer lines, but they require resources, tooling, labors. H. Kursad et al. investigated the FDM 3D printing of MWCNT reinforced ABS nano-composite parts, highlighting the significant improvement in mechanical and electrical properties, such as increased tensile strength, flexural strength, and electrical conductivity, demonstrating the potential for improved ABS parts in the electronics, aerospace, and automotive industries [10].

3.2. Emergence of Cavity

It is also known as voids or defects; they can appear for a variety of reasons and have an effect on the quality and structural integrity of printed products. Cavities may develop between deposited layers if the material flow is not properly controlled or if there are problems with the material's viscosity, temperature, or extrusion pressure. During the printing process, uneven or inconsistent heat distribution might result in localized cooling or restricted material melting. This may cause gaps or weak interfaces between the printed layers due to insufficient layer fusion. Powdered material is used in several AM procedures, such as powder fusion methods in which the internal cavities may be created in the printed part if gases or air pockets get trapped in the powder bed or the material feedstock.

4. Fused deposition modeling:

The additive manufacturing process is the manufacturing process in which we get the desired shape and size of an object, efficiently with the least usage of material forming it layer by layer which ultimately generates the desired outcome product by any material, from polymers to metals and from ceramics to even a biological material too such as living cells. The founder of Stratasys, Scott Crump first introduced the FDM process to the world in the late 80s. It is well known by some other names like Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF), Plastic Jet Printing (PJP), Material Extrusion (ME), and Extrusion Deposition (ED). The study examines the flexural and tensile behavior of 3D printed objects made of PLA, ABS, and PLA-ABS blends, emphasizing the impact of processing variables, such as printing orientation, layer thickness, and infill density, on the mechanical characteristics of the materials. The maximum flexural strength was found in PLA, the highest tensile strength was found in ABS, and the qualities of PLA-ABS blends were intermediate, highlighting the significance of choosing a material and processing conditions depending on desired mechanical attributes. In order to better understand and optimize the qualities of 3D printed parts, the study also highlights the major impact of printing orientation on mechanical properties and proposes more research on other processing factors [11].

In 3D printing, the moving nozzle extrudes the heated material and deposits it on the bed which can move in a vertical direction that is the same as the layer thickness. The nozzle can move in both directions x and y, it moves in x-y while printing a single layer and it continues till the entire object is printed. The material is heated slightly above its glass transition or Softening temperature which brings it to a semi-solid state [13]. After extrusion through the nozzle, the material immediately solidifies and a cohesive phenomenon takes place which ultimately strengthens the object to be printed. The adhesive phenomenon takes place between the bottom layer and the bed surface which ensures that the object does not shift out of position. Depending on the application of the object the printing parameters are selected. In the 1990's, FDM became commercially available, and its basic operational principles were depicted in diagram by H.K.Dave et.al. [12] is illustrated in fig. 1

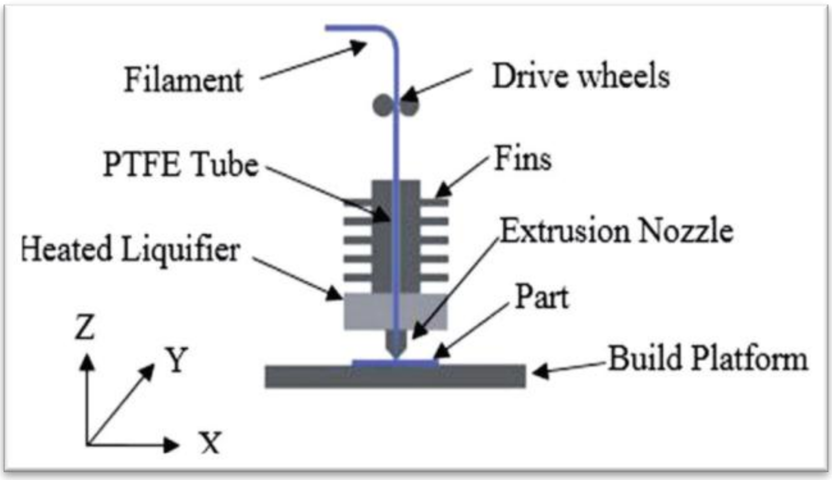


Fig-1: FDM System

5. Process Parameters of FDM

In FDM, process parameters are very important since they have a direct impact on the precision, quality, and characteristics of the printed parts. Some of the most important factors are orientation, infill pattern, infill density, layer thickness, printing speed, fiber angle, number of fiber rings, extrusion temperature [5,7,12]. Depending upon the particular needs of the printed part, the filament being used, and the desired quality of finished result, these process parameters can be modified and optimized. To improve print quality, dimensional accuracy and mechanical qualities in FDM, these parameters can be fine-tuned._Vinaykumar S Jatti et al. investigated the effect of Fused Deposition Modelling process parameters such as layer thickness, printing speed, infill percentage, and extrusion temperature on the mechanical properties of printed parts, where printing speed affected material distribution and physical wear, infill percentage influenced tensile strength, impact strength, flexural strength, and surface roughness with maximum values observed at 100% infill density, and layer thickness influenced tensile strength, impact strength, flexural strength [13]. Ashish R. Prajapati et al. investigated the impact strength of 3D printed fiber reinforcement polymer composites and discovered that the number of fiber rings has a significant influence, with increasing impact strength observed in 0°/90° fiber angle samples, highlighting the potential of 3D printing for producing functional designs with improved mechanical properties in various industries such as aviation and automotive [14].

5.1. Layer Thickness

The layer thickness is the height of each layer that is extruded from the nozzle and deposited in FDM. This is one of the most important parameters which plays a role in deciding the precision level sharpness of the 3D printed object. The smaller the layer thickness more will be the smoothness of surface finishing and greater the precision but ultimately it will increase the printing time and material required for FDM whereas, the larger layer thickness prints the model in faster rate but compromises in the surface finishing quality. Fig 2. illustrates the different layer orientations. The mechanical, surface, and part qualities are all influenced by the layer thickness. The density of the component and surface quality rise with layer thickness [15]. Higher tensile strength is attained at a lower layer height because a bigger bonding area with fewer vacancies is detected at the lower layer height, which improves the performance of the test specimen [16]. With the increment of the layer thickness, tensile strength first increases, but after a further increase in layer thickness, tensile strength was found to be decreased [17].

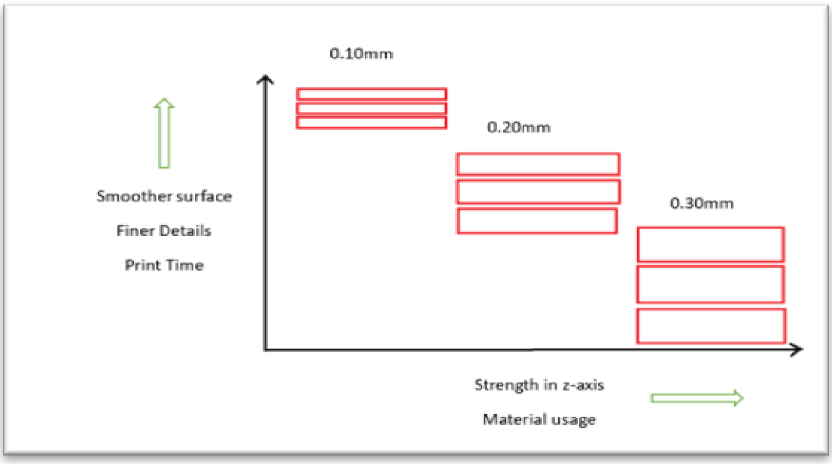


Fig-2: Graphical representations of various layer thickness

5.2. Orientation

The orientation refers to how the specimen is printed along any axis on the bead. In this study we have taken three different orientations viz., flat, on long edge and on short edge. In flat orientation the specimen is printed along the bottommost layer and gradually prints the upper layers, while in on long edge orientation the specimen is to be printed along the longest side of the specimen (horizontally) and similarly for short edge it is printed along the shortest side of specimen (vertically). The cooling rate, layer packaging and tensile strength varies as per the different orientations. Fig 3. refers to different orientation for dog bone shaped specimen.

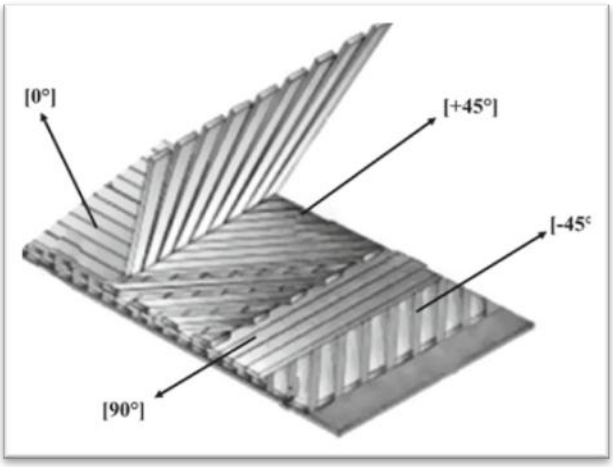


Fig-3: Schematic of fiber orientations

5.3 Infill Density

Infill density refers of the part is the percentage volume that is being filled while printing the specimen and the remaining space is void. The infill density affects the characteristics like strength, material usage, weight of specimen, time of print. The lesser the infill density the lesser will be the values of above characteristics and more the value of infill density more will be the value of all characteristics. Fig 4 illustrates the various combinations of infill density along with infill patterns [12].

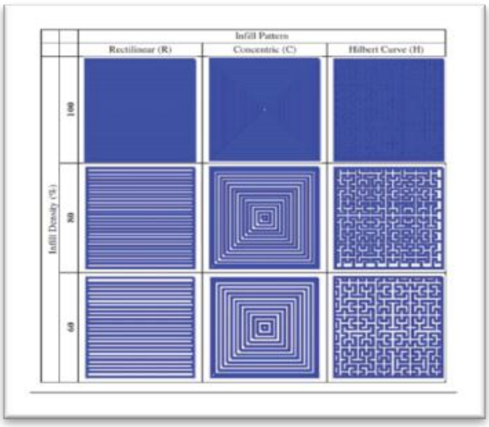


Fig-4: Infill density vs Infill pattern

5.4. Infill pattern

The infill pattern is the technique that how the inner layers are bounded to each other. These are nothing but geometrical patterns which are being printed in the inner structure. There are many infill patterns available and those are selected as per the application requirements of an object. More the complexity required in the infill pattern more time and material it will take for printing as shown in fig.4.

5.5 Printing speed

The rate at which the printer extrudes and deposits the filament material to produce a three-dimensional object is referred to as printing speed in FDM. It is a critical factor which can affect the overall effectiveness, productivity, and quality of process. High speed causes Improper Distribution of material & wear of physical parts Very low speed causes lot of time to print a single specimen [13].

5.6. Extrusion Temperature

The extrusion temperature in FDM is the temperature at which the thermoplastic filament is melted and deposited one layer at a time to produce a 3D printed object. The extrusion temperature in FDM has a significant impact on variety of printing related factors as well as the final print quality. The filament must consistently melt at the extrusion temperature in order for it to flow easily through the printer's nozzle. The filament may not completely melt if the temperature is too low, which could lead to blockages or uneven extrusion. The resolution and general print quality are impacted by the extrusion temperature. It affects the deposition of material, flow rate, and filament viscosity. Although a higher temperature can make the material more flowable, it can also cause problems like stringing or excessive filament oozing. However, a lower temperature may cause under- extrusion or insufficient layer bonding while producing prints that are more accurate.

5.7. Raster Angle

Raster angle is the angle created by the X-axis of the platform where layer deposition occurs during printing. The mechanical characteristics of 3D-printed items are significantly influenced by the raster angle, which demonstrates that tensile strength declines with increasing raster angle. A raster angle of 0° may offer greater tensile strength but also more brittleness. While a 45° raster angle loses stiffness and tensile strength, it enables for greater elongation. The best raster angle should be chosen taking into account the required balance between strength, flexibility, and other important characteristics for the particular application. Parts constructed with a 90° raster angle had decreased stiffness and tensile strength [18] . The tensile strength is significantly affected by raster angle. As the raster angle is changed from 0°-45°-90° the tensile strength goes on decreasing. At 0° raster angle, all fibers are deposited parallel to the loading direction, allowing them to bear higher load since the impact of fiber bonding is minimized. When the raster angle is 90°, all of the fibers are deposited perpendicular to the tensile stress, resulting in lesser strength. Tensile stress and failure occur at a 45° raster angle owing to shear between the fibers and fiber fracture [16]. When the raster angle is changed from 0° to 90° level, the tensile strength first decreases and then increases [17].

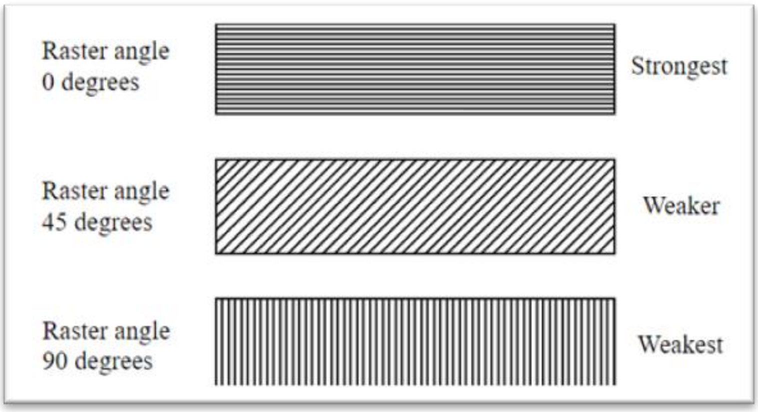


Fig-5: Raster Angle

5.8. Raster Width

In 3D printing, raster width refers to the width of each individual line, or "raster," deposited by the printer nozzle during the printing process. It is often referred to as line width or extrusion width. It determines how much material is extruded and deposited with each pass of the printing nozzle. A greater amount of material is deposited with a larger raster width, resulting in thicker printed lines. In contrast, a narrower raster width indicates that less material is deposited, resulting in thinner printed lines [18]. It is observed that as raster width increases, tensile strength decreases [17]. Higher tensile strength has been obtained with a higher value of the raster width [16, 20]. Fig 6 shows the raster width along with raster to air gap [19].

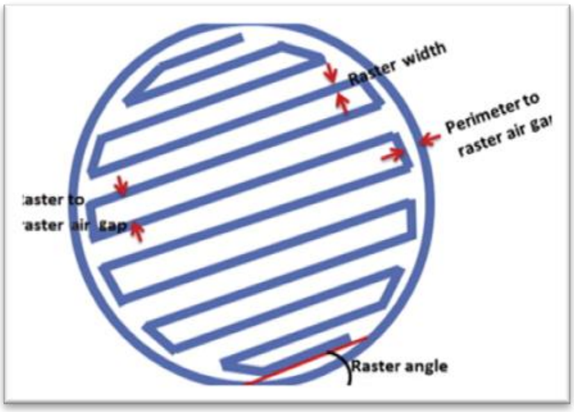


Fig-6: Raster Width

6. Composite material and reinforcements

Sithiprumnea Due et al. performed research on the creation and use of ABS/carbon nanotubes (CNTs) composite filaments in FDM 3D printing, demonstrating that the addition of CNTs improves the thermal stability, modulus of elasticity, and mechanical properties of the composite filaments, suggesting their potential as materials for FDM 3D printing and highlighting the need for further optimization of printing parameters and exploration of other properties like elastic modulus [21]. Thai-Hund Le et.al. demonstrated that the incorporation of MWCNTs into ABS filaments for FDM 3D printing improved the thermal and mechanical properties of the composite, with uniform distribution of MWCNTs observed, suggesting their potential for high-performance functional parts, although further research is required for process optimization and long-term stability evaluation [22]. The study demonstrates how adding reinforcement materials, increasing reinforcement content, improving part orientation, and modifying infill patterns and densities can improve the mechanical properties of composite parts made using fused deposition modelling (FDM) technology. This highlights the potential of FDM for creating composite parts with improved mechanical properties through process parameter optimization [23]. This study examines how process variables affect the mechanical characteristics of Nylon-Aramid composites made using FDM. The Taguchi method is used to optimize variables like nozzle temperature and infill density, which leads to improved tensile and flexural strength due to improved interfacial bonding and optimized microstructure [24]. This review highlights the effects of printing parameters, material properties, and composite filaments on product strength, stiffness, and other mechanical properties while highlighting the need for further optimization to improve the mechanical properties of FDM-printed parts. It also offers an overview of research on the production of metal/polymer composite filaments [25].

7. Conclusion

In this review paper, enhanced comprehension of the effects of FDM process parameters and linked features parts printed by FDM were formed. These process parameters are regarded as essential because the printed part surface quality, strengths, aesthetics and overall efficiency of the FDM process is determined by them. Various processing parameter's effects have been evaluated, and one of them, it is noticeable that orientation of parts to be printed is considered to be an inevitable factor in determining the mechanical strength of part. It is observed that infill density plays a dominating part in deciding the weight and cost of the material to be printed, there is a huge possibility for doing research activity in these parameters as the present examination are mainly conducted for the value's standard values and types. It is seen that infill pattern plays a main role in deciding the mechanical strength and generally it is maximum for symmetrical structures. It is evident that layer height has a notable influence on material usage and quality of printing. The fundamental variables are receiving great deal of attention from researchers, yet numerous unknown factors must still be looked into as they have the potential to have a big impact on both the effectiveness of the procedure and the quality of the final output. The lack of substantial literature support regarding the impact of environmental factors like temperature, humidity, filament manufacturing conditions suggests a considerable opportunity for further research in this particular field.

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