Materials Science

AIMS Materials Science, 11(5): 950–990.
DOI: 10.3934/matersci.2024046
Received: 23 June 2024
Revised: 07 September 2024
Accepted: 05 October 2024
Published: 17 October 2024

http://www.aimspress.com/journal/Materials

Review

A recent review on advancements in dimensional accuracy in fused deposition modeling (FDM) 3D printing

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Abstract: Fused deposition modeling (FDM) fabricated components have gained significant attention and widespread adoption across modern industries due to their versatility, serving as both prototypes and final products. FDM offers rapid and cost-effective prototyping and production capabilities; however, utilizing directly manufactured FDM parts is not practical. Secondary operations like post-processing, testing, and validation are typically required to ensure that the fabricated parts meet the necessary standards for their intended applications. Desired repeatability, reproducibility, reliability, and preciseness should be the main prerequisites of the part fabricated. It is desirable that additive manufacturing (AM) products should be produced with advanced control processes which should possess acceptable quality characteristics. Ensuring the dimensional accuracy of FDM parts is very crucial, and hence it is important to emphasize the key factors that influence the dimensional precision during their fabrication. Sharing insights into these critical factors is essential to steer scholars, researchers, and the AM industry towards informed decisions and future advancements in AM. We aimed to outline the significant factors influencing the dimensional accuracy of the FDM part. These research papers are collected from Scopus and web of science data using "FDM" and "dimensional accuracy" as the keywords. We include the latest papers published especially during 2020 to 2024, which were lacking in earlier research.

Keywords: additive manufacturing; fused deposition modeling; layer adhesion; quality; accuracy

1. Introduction

Additive manufacturing (AM) techniques utilize digital information of a part to produce it using a layer-by-layer deposition process, all managed by a computer-controlled system [1]. Since inception, AM industries have shown tremendous growth, and it was estimated that AM has shown almost six times the growth during the 2000s when compared with its growth in the 1990s [2,3]. AM techniques have great potential to be used in various ideal applications. Wohlers Associate report presented in 2013 reflected that AM system sales revenue contributed 19% in industrial products, consumer products (18%), automotive (17%), medical (14%), aerospace (12%), and military products as 5%. The automotive, medical, aerospace, and military sectors require high precision and reliability, leading 48% in total. The global AM market sales was $2.2 billion in 2012, $16.72 billion in 2022 and its market size is forecasted to grow up to $76.16 billion by 2030 [2–4]. AM techniques are proficient of a rapid production of any complex geometries with less product cycle time [5,6] with negligible tools usage and almost no human involvement. AM techniques are capable of producing tailored products with intricate geometries in minimum production time with less waste or scrap. AM application reduces the surplus expenditures in product development and can generate parts with high strength to weight ratio [7]. Application areas of AM include aerospace, automobile, construction, prototyping, and casting. The ability to tackle variability, volume and delivery time constraints in the best possible manner, especially on-demand production scenario, makes this technology the best candidate to tackle the challenges emerged from the current scenario [8]. As per ASTM F2792-12a [9], AM processes are categorized into seven different categories. Table 1 provide brief description of seven AM processes. The detail of the processes can be found elsewhere in literature [10].

Fused deposition modeling (FDM) is an important extrusion-based method, where thermoplastic materials are extruded in pasted form and deposited as layer by layer in a controlled platform, gradually building up a three-dimensional object. The detailed methodology of FDM is discussed in section 1.1.

1.1. FDM

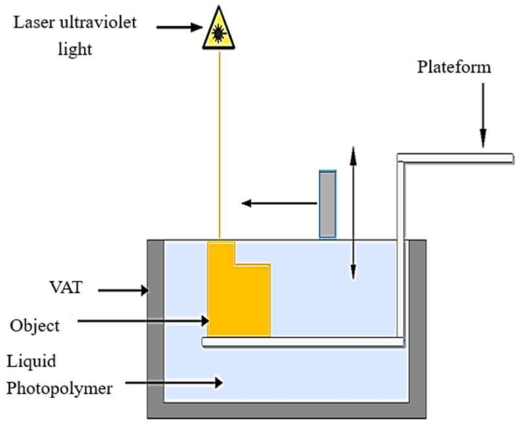
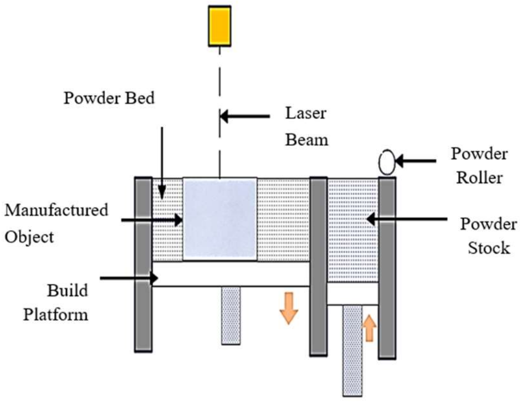
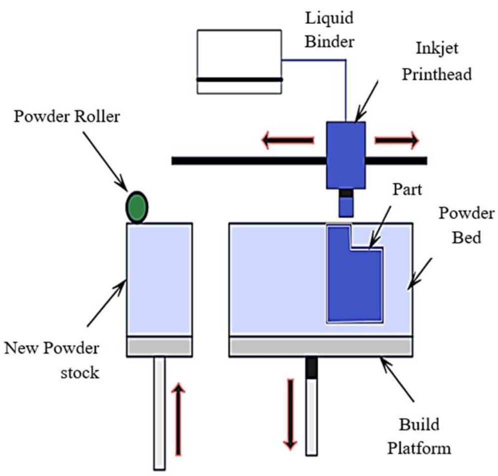
Fused deposition modelling is a popular additive manufacturing process also referred as fused filament fabrication (FFF), which falls under the category of material extrusion as per ASTM F2792-12a mentioned in Table 1. Here, parts are fabricated by precisely depositing melted material (in liquefier) on a platform as predefined path [11]. The platform or table is free to move along Z-axis. FDM is the most extensively used AM process and it is presumed as the first process when someone thinks of AM technology.

The materials for fabrication include thermoplastics such as ABS (acrylonitrile butadiene styrene), PC (polycarbonate), ABSi (a high-impact grade of ABS), PC-ABS, polylactic acid, polycaprolactone, polyether ether ketone, polyhydroxyalkanoate, and others. These materials are used owing to their advantages as mentioned under:

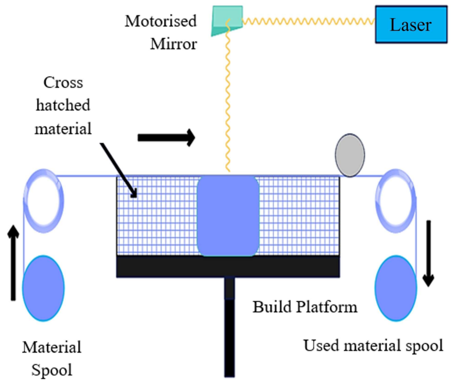
1. ABS is preferred for its strength and durability, while polycarbonate offers superior impact resistance and thermal stability.

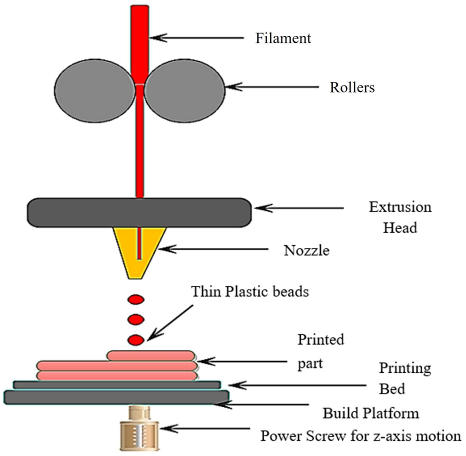
2. ABSi enhances the impact resistance of traditional ABS, making it suitable for more demanding applications.

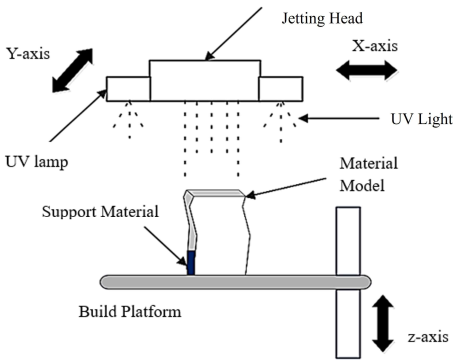
Table 1. AM process as per ASTM F2792-12a.

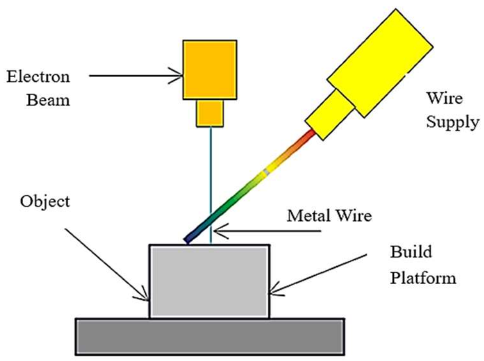
Process	Brief summary
 VAT photopolymerization.	Here, liquid photopolymer like acrylates and resins in a vat are selectively cured by light-activated polymerization.
 Powder bed fusion.	They use thermal energy of laser to fuse the metal powder like steel, aluminium and copper placed in powder bed.
 Binder jetting.	Powder materials are joined in these methods by depositing a liquid bonding agent over it.

Continued on next page

<table>
<tr><th>Process</th><th>Brief summary</th></tr>
<tr><td>

Sheet lamination.</td><td>Sheets of materials are bonded by adhesives to form an object.</td></tr>
<tr><td>

Material extrusion.</td><td>Materials in these methods are extruded from nozzle or orifice onto the platform.</td></tr>
<tr><td>

Material jetting.</td><td>Here, droplets of build material are selectively deposited over each other.</td></tr>
<tr><td>

Direct energy deposition.</td><td>These methods use energy sources like laser and electron beam to fuse materials by melting them as they are deposited one over another.</td></tr>
</table>

1. PC-ABS combines the best qualities of both polycarbonate and ABS, providing a balanced mix of strength, flexibility, and heat resistance.

2. Polylactic acid (PLA) is known for its ease of use and environmental friendliness.

3. Polycaprolactone (PCL), offer low melting point and bio-degradability; polyether ether ketone (PEEK) is recognized for its exceptional mechanical properties and resistance to high temperatures

4. Polyhydroxyalkanoate (PHA) is a biodegradable option that emphasizes sustainability.

Sometimes these materials are mixed with fibers for high performance. These thermoplastics can be classified based on their mechanical properties, thermal resistance, and environmental impact, allowing for tailored material selection based on the specific requirements of the fabrication process. Important parameters greatly influencing the quality of the part are process parameters like layer thickness, part build orientation, raster angle, raster width and air gap, print speed and etc. [12,13]. Additionally, other factors that affect the quality of FDM parts are material properties, temperature settings, slice settings, and post processing conditions. FDM can build parts according to layer thickness provided in machine specifications. For example, FDM Vantage SE by Stratasys built part in three available layer thicknesses that are 0.127, 0.178, and 0.254 mm [14,15]. Important process parameters of FDM are listed in Table 2 and stages of part fabrication is explained in section 1.1.1. with schematic diagram as shown in Figure 1.

Table 2. Significant process parameters of FDM.

Process parameter	Definition
Part fill style	Determines the fill pattern used to build a solid model. It is of two types: 1. Perimeter/rasters: generates a part fill comprising one outer contour and internal raster filling. 2. Contours to depth: the part is filled using an outer contour, internal contours, and internal raster fills. The number of extra contours depends on the depth of the contour value.
Contour width	The width of the tool path surrounding each curve of the part. Each curve of the part is filled using at least one contour.
Part *X*-*Y* shrinkage factor	The factor used to adjust for shrinkage on the horizontal plane (*X*-*Y* plane).
Part *Z* shrinkage factor	The shrinkage factor applied in the *Z* direction.
Perimeter to raster air gap	The gap between the innermost contour and the boundary of the fill pattern within the outline.
Layer thickness	Defines the thickness of each individual layer of material that is deposited to build up the final 3D printed object.
Orientation	Build orientation refers to positioning of the object on the print bed in relation to the printer's nozzle, which impacts its strength, surface finish, and quality.
Raster angle	It is a direction of raster relative to the *X*-axis of build table.
Raster width	Width of raster pattern used to fill interior regions of part curves
Air gap	It is the gap between two adjacent rasters on same layer.

1.1.1. Part fabrication

Part fabrication is done in six separate stages, as defined in Figure 1. The part fabrication starts with the creation of a 3D CAD (3-dimensional computer aided design) model of the part using any drawing software like AutoCAD, Pro-E (Pro/Engineer), CATIA (computer ided Three-Dimensional

Interactive Application) etc. The 3D CAD model is then converted to a .STL file format, which is a machine acceptable format. STL file is transferred to AM processing software like Insight^{TM} for FDM Vantage machine. Here, process parameters, part material requirement, build time, shrinkage, distortion, surface quality, and material cost are defined. The need for support structures in various locations and orientations, especially for complex and intricate geometries with features like overhangs, internal cavities, and thin walls, is also determined. The STL model is divided into multiple slices according to the chosen layer thickness, and a tool path is generated for each layer. Next stage is stage where actual part fabrication happens. The schematic of machine hardware is shown in Figure 2. The details of the process can be found elsewhere in literature [12,16–19]. Once the part is fabricated, the post-processing is carried out where, the fabricated part is removed from the build chamber, and any support material is manually removed or sometimes eliminated using vibrations in an ultrasonic bath.

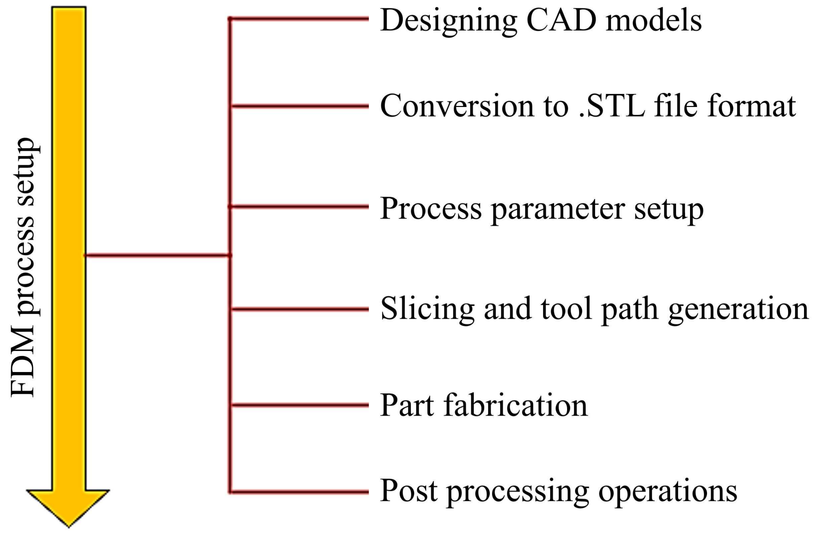


Figure 1. Stages in fused deposition modeling process.

FDM technology can produce highly complex parts quickly, without the need for specific tooling or detailed process planning, using only digital part information [20]. Functional parts with outstanding resistance to heat and chemicals and impressive strength-to-weight ratios, can be manufactured [21]. Some of other vital advantages includes absence of post curation, possibility of manufacturing very large pieces without deformation and possible of combining materials during fabrication. Application areas include automobiles, medical, pattern for casting, aeronautics, electrode manufacturing for electrical discharge machining, etc. [22–24]. It is believed that with the progressive development in material science, high-performance polymers with superior mechanical properties and thermal stability, integrating more sophisticated calibration and control systems can be used to achieve tighter tolerances and better surface finishes. Incorporation of real-time monitoring and feedback mechanisms can be used to ensure consistent quality throughout the printing process. AM technologies suffer from limited materials, restricted size, and design inaccuracies. All these limitations can address through post processing operations as improvement in post-processing techniques can enhance the precision and reliability of printed parts. Additionally, implementation of rigorous quality assurance procedures is required to meet the stringent standards of aerospace and automotive industries.

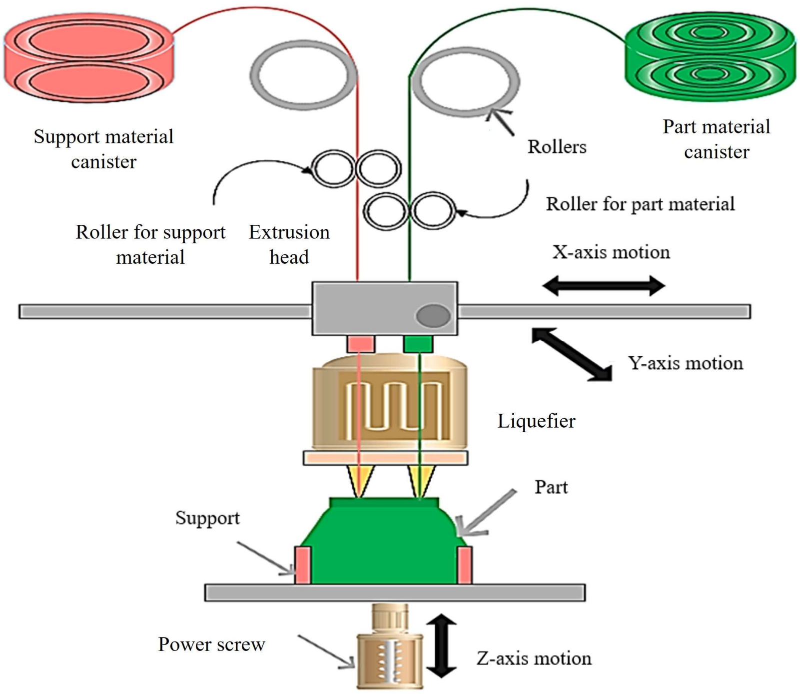


Figure 2. Schematic of FDM machine.

To enhance FDM technology for high-precision and high-reliability applications in aerospace and automotive manufacturing, several key improvements can be pursued. These include advancing material science to develop. Additionally, refining post-processing techniques to enhance the precision and reliability of printed parts can address the stringent requirements of these industries, ensuring that FDM parts meet the rigorous standards of aerospace and automotive applications.

Performance measures of AM techniques include quality characteristics, mechanical properties and manufacturing conditions. A quality characteristic includes dimensional accuracy, surface roughness, warping and layer adhesion. Ensuring the dimensional accuracy of FDM parts is paramount and highlighting the key factors that impact this crucial aspect is essential. Important factors affecting dimensional accuracy are raster angle, air gap, raster width, build orientation, and layer adhesion [25–32]. Providing insights into these critical factors is vital to guide scholars, researchers, and the AM industry towards well-informed decisions and future advancements in AM technology. This research aims to outline the impact of these significant factors on the dimensional accuracy of FDM parts through a comprehensive review. The research papers for review were collected from Scopus and Web of Science databases using "FDM" and "dimensional accuracy" as the keywords. The focus is on the latest papers published between 2021 and 2024, addressing gaps in earlier research endeavors.

It is important to mention that similar studies were presented earlier [21,33–36] however, recent researches pointed many additional factors affecting the dimensional accuracy of FDM parts. A recent review is thus required, which is believed to benefit the scholars and researchers to completely understand the theory and reasoning behind the part's inaccuracy of FDM and accordingly the process parameters can be wisely selected. It also helps them to correlate the results established by earlier researches with the findings of the recent researches. We focused on the latest papers published specially during 2021–2024 which were lacking in earlier researches. The paper is arranged in five sections. In the first section, principle and basic methodology of FDM was presented. In the second section, we provide the importance of dimensional accuracy in FDM fabricated parts. In section 3, we discuss important studies pertaining to the dimensional precision of FDM components performed (critical studies before 2019 and important studies after 2019). In section 4, we provide the findings and discussions drawn from the collective research study. Concluding remarks and challenges are presented in section 5.

2. Importance of dimensional accuracy in FDM processes

Dimensional accuracy in FDM is very crucial due to its direct impact on the functionality, performance, and overall quality of printed parts [37,38]. Few of the critical aspects defining the importance of dimensional accuracy in FDM are:

1. Functional performance: in engineering, medical, and aerospace application, precise dimensions are pre-requisite for functional performance [39]. It is very important to mention that deviations in dimensions can directly impact the functionality of the final product, whether it is confirming parts fit in an assembly or meeting specific tolerances for mechanical components. Moreover, minor differences in dimensions can lead to misalignments or failure of moving parts.

2. Prototyping and iterative design: FDM is extensively used for rapid prototyping and iterative design processes [40]. To evaluate form, fit, and function of prototypes, accurate dimension must be ensured by designers and then only they can move to production stage. Inaccuracies in dimensions can result in inaccurate estimations which can lead to expensive design revisions and delay in the product development cycle.

3. Compatibility with existing parts: in numerous cases, FDM parts are required to integrate with components or systems. Ensuring the compatibility and interchangeability relies on the dimensional accuracy [41]. For ex- in a vehicle manufacturing, components produced through FDM must align with other existing parts of the vehicle to maintain structural integrity and performance.

4. Cost and material savings: material usage and printing time is also directly influenced by the dimensional accuracy of the part. Dimensionally inaccurate parts may require surplus material to compensate for shrinkage or errors, which increased the material costs and printing times. Dimensionally accurate parts minimize material wastage and optimizes the printing process, thereby reducing the cost [42].

5. Surface finish and aesthetics: dimensionally inaccurate parts also have indirect effect on surface finish and aesthetics. Inaccurately fabricated part can result in surface imperfections, warping, or layer misalignments, detracting from the overall appearance of the printed part. Dimensionally accurate FDM parts shows smoother surfaces and finer details, enhancing their visual appeal and usability [43].

6. Regulatory compliance and quality assurance: dimensional accuracy is a key parameter in meeting strict regulatory requirements and quality standards in important industries like aerospace, automotive, and healthcare [8,44]. FDM parts must meet precise dimensional tolerances to guarantee safety, reliability, and consistency in performance.

7. Customer satisfaction: dimensional accuracy meets the customer satisfaction, trust and loyalty and also protect the brand reputation. Conversely, dimensional inaccuracy can lead to dissatisfaction, returns, or even safety concerns, ruining the reputation of both the manufacturer and the technology.

Therefore, it can be inferred that dimensional accuracy is crucial for the effectiveness and feasibility of FDM technology in diverse industries. By prioritizing on dimensional precision, full potential of FDM can be unlocked by the manufacturers for production and innovation, guaranteeing reliability, efficiency, and customer satisfaction [45,46].

3. Literature survey

The quality of FDM fabricated part is mainly defined by parts dimensional accuracy, surface finish, warpage and adhesion between layers. In this section, significant research findings concerning the dimensional accuracy of FDM parts are presented. It has been observed that since 2001, numerous papers linked with accuracy of FDM parts are published and the number of these published papers on yearly basis is displayed in Figure 3 (source: Scopus database). Figure 4 categorized these published papers by the platform of their publication. It can be observed from Figure 3 that although number of related publications are available between 2001–2023, but the majority of the papers are published in 2018 and onwards. To generate a solid conclusion, few highly cited papers published before 2021 and their findings are correlated with various recent researches conducted after 2020 which is lacking in earlier reviews.

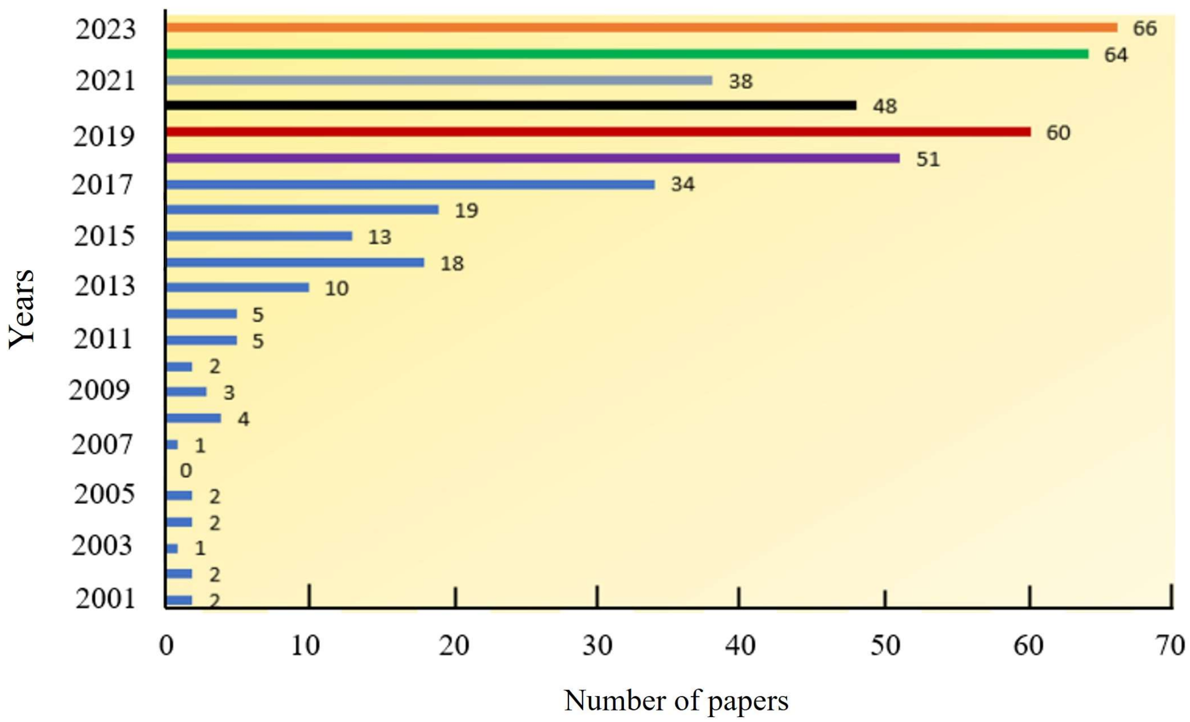


Figure 3. List of DA related FDM papers published year wise (source: Scopus).

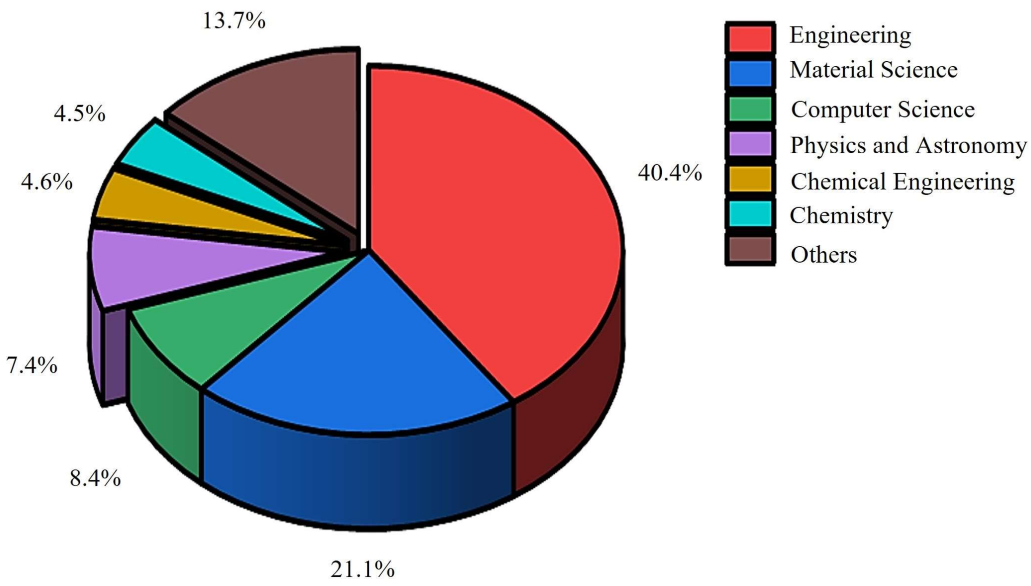


Figure 4. List of DA related FDM documents published platform wise (source: Scopus).

3.1. Investigations on FDM's dimensional accuracy before 2020

A benchmark study was executed by Kim and Oh [47], where the researchers compared the geometrical and part's dimension accuracy (DA) of various AM processes. The geometric features and data for AM parts were collected using the point clouds, measured from the non-contact 3D scanner. The deviations between measured data and data given to CAD models were then compared.

For FDM fabricated part, it was observed that the accuracy in milli-scale was very poor, owing to thick layer deposited, wide scanning interval and larger radius of extrusion nozzle. It was therefore suggested that FDM technology is unsuitable for fabrication of small parts. They also proposed that the part's accuracy is dependent on the given dimension and geometry. Sood et al. [48] experimentally investigated the impact of five important process parameters: layer thickness, part orientation, raster angle, air gap, and raster width on the DA of FDM fabricated ABS P400 part. They found that part shrinkage was the major reason leading to inaccuracy in the build part along the length and width direction. A positive deviation value is observed in the thickness direction, and it was observed that optimal factor settings for each performance characteristic are different. A multi-response optimization was conducted utilizing the Grey Relational Analysis (GRA) integrated with the Taguchi Method to determine the optimal single-factor settings for fabricating a part. The objective was to minimize dimensional inaccuracies along on the length, width, and thickness of the part [48]. Turner and Gold [49] reviewed the researches linked with the DA and surface roughness for FDM parts and other related extrusion-based AM processes. A study was carried out with an intent to find the dependency between process and design parameters and the DA of the parts. The method used for part fabrication was also evaluated. They determined that thermal distortion and material shrinkage are the primary factors contributing to dimensional error in FDM fabricated parts. They also claimed that their review was first to highlight the dimensional accuracy and surface roughness in extrusion-based printing. A novel method of shape memory polymer (SMP) processing for AM, in particular for FDM was presented by Yang et al. [50]. The researchers investigated key extrusion parameters to develop SMP filaments and examined the effects of extrusion temperature and scanning speed on print quality. Using a Coordinate Measuring Machine (CMM) with the relative error method, it was found that increasing extruder temperature raised dimensional inaccuracies due to higher material liquidity, making control difficult. Conversely, at lower temperatures, incomplete melting, and high friction during extrusion also led to increased errors. The recommended extrusion temperature range for optimal SMP printing was 220 to 240 °C. Additionally, slow extrusion speeds led to poor heat dissipation and instability in the printed layer while fast speeds caused vibrations that also increased errors. To the best of authors knowledge, SMPs should be evenly distributed within the filament to achieve consistent performance. Layer bonding during printing should be to ensure to handle the shape memory effects without compromising the part's structural integrity. Use of self-healing material like self-healing polymers, hydrogels, rubber, and silicon are also suggested as these materials possess the ability to repair damage autonomously, which can improve the longevity and durability of FDM parts. Process parameter optimization of self-healing materials find the optimal combination that supports the self-healing characteristics while maintaining dimensional accuracy.

Impact of part orientation on DA of FDM parts built at seven different part orientations about Y axis by was investigated by Garg et al. [51] with and without post building chemical vapor treatment. It was observed that minimum dimensional deviation of parts was observed when surfaces of the FDM part was orientated either parallel or perpendicular with respect to the axis of a part. Further, they proposed that chemical treatment of the build part reduced dimensional deviation in many cases. Alafaghani et al. [52] studied the impact of extrusion temperature, layer thickness, infill patterns, and the infill percentage on the DA of PLA samples. They measured the parts' linear dimensions, along with volume and mass, and compared them to the CAD model. They observed that FDM technique fabricated oversized part when compared to CAD model of the proposed part. Geng et al. [53] proposed that the dimension of printing specimens was dependent on the extrusion speed and printing speed. It was suggested that improper synchronization between printing speed with extrusion speed would create several issues related to unstable dimensions of the printed samples. Moreover, an established relationship of extrusion speed and filament diameter into the extrusion control algorithm is required for better accuracy. Dey and Yodo [54] conducted a survey on parametric optimization and studied the effect of parameters on the characteristics of FDM parts. A general understanding on existing researches carried out on FDM process parameter optimization using different optimization methods was highlighted. The research showed that FDM parameters are interrelated and each parameters have their own significance on part characteristics. The key findings of the survey were: (1) PLA and ABS are the two most widely used materials; (2) FDM parameters like infill pattern, print speed, shell width, or extrusion temperature are less investigated as compared to other common parameters used for research studies; (3) Limited number of researches optimized multiple parts characteristics simultaneously; (4) The FDM process is complex each step has different levels of uncertainty; (5) Uniformity of FDM fabricated parts can be enhanced by considering uncertainties during design and manufacturing; (6) They proposed that more studies should focus on least investigated parameters for future research directions. Earlier studies also showed that volumetric shrinkage is the key reason for dimensional inaccuracy in FDM manufactured prototypes. In the similar direction, Dambatta et al. [55] applied ANFIS modeling approach for prediction of volumetric shrinkage in FDM process. They selected the layer thickness, orientation angle, and structural geometry to estimate the volumetric shrinkage in the *XZ* and *YZ* axes using ANFIS. Effectiveness of ANFIS model was validated using experimental results, which showed 3.15% average prediction error. They showed that same result can be used for manufacturing of the hollow shapes in the components. Beniak et al. [56] investigated on the shape and DA of FDM fabricated parts. They recommended that ANOVA (Analysis of Variance) and average values from tolerance and dimension measurement showed that the printing temperature have the significant impact on the shape and dimensional tolerance of FDM produced parts. Higher temperature increased the liquidity of the material and material flow is easy. There is possibility of material flow towards side due to higher liquidity and gravity; thus, dimensions and tolerance are inaccurate compared to specimens produced at low temperature. Research by Ansari and Kamil observed that material fluidity directly impacts the extrusion flow and hence the final part's dimensional accuracy. Hence, they suggested to maintain the extruder temperature within a specific range to balance material fluidity and print accuracy. A stable and controlled heating environment for the extruder was proposed to avoid overheating or underheating. It was also recommended to use cooling fans to solidify the extruded material quickly, which helps in reducing stringing and improving surface finish. However, cooling rates must be carefully monitored as too much cooling can cause warping or poor layer adhesion. Cattenone et al. [57] used FEA to simulate the AM based FDM process for prediction of distortion and comparison with experimental data. They proposed that the meshing strategy plays a critical role in replicating the actual printing process. To investigate the local effects, a finer meshing strategy was proposed for small models, whereas, for large models, in which the local effects are negligible, a coarser meshing strategy was recommended. Here, small and large refer to the models' dimensions when compare with the filament dimensions. Alhijjaj et al. [58] explores the effect of FDM parameters on quality of pharmaceutical solid dosage forms. The study presents the results of examining several crucial process parameters of FDM and their influence on quantifiable, pharmaceutically significant quality measure. Within the scope of the study, printing speed emerged as a more influential factor affecting weight consistency and dimensional accuracy of the printed dosage forms compared to printing temperature. Moreover, printing temperature and the characteristics of the build plate surfaces were identified as significant factor to first layer effect layer extrusion (FLE). Peng et al. [59] conducted a study on the impact of printing parameters for the surface quality and microstructure of PEEK. The research findings indicate that a higher heating temperature of 440 °C, a printing speed of 20 mm/s, and a reduced printing layer thickness of 0.1 mm can enhance the density of PEEK components, reduce the internal defects, boost the adhesion between 3D printed layers and infill filaments, and alleviate surface roughness. These efforts help improve the development of better 3D printing methods designed for PEEK. Mora et al. [60] explored the impact of FDM process parameters in the dimensional characteristics of fabricated ABS parts using reverse engineering techniques. Use of reverse engineering and 3D scanner showed that better products can be made by FDM technology. They also proposed that treating the surface with chemicals can make the parts smoother. The tests conducted in the study quickly and easily obtained measurements like dimensions and tolerances. This method could be used in industries easily, quickly, and cheaply, letting the researchers to analyze complex parts in detail, both small and big. Some critical research up to 2019 and their related findings are presented in section 3.1.1.

3.1.1. Critical findings on FDM's dimensional accuracy before 2020

As outlined, we focus on research conducted and published from 2020 onward. Despite the availability of numerous studies presented prior to 2020, section 3.1. selectively highlights works that are highly cited in research. To establish a comprehensive understanding and facilitate the correlation of research outcomes with previous findings, we present critical insights from important papers published before 2020 in this section. This approach provides a broader historical context, highlighting how earlier research has shaped and influenced current trends and discoveries. Shrinkage was observed as one of the primary reasons for inaccuracy of FDM fabricated ABS P400 part along length and width. However, an increase in thickness was observed compared to expectation [48]. It was also observed that optimal factor settings for each performance characteristic are different. This was suggested to convert multiple output into one response using multi-objective optimization method (GRA) and suggest optimal factor setting for fabricating part with minimized dimensional inaccuracy. Temperature range between 220 and 240 °C was suggested as the appropriate temperature range for printing shape memory polymer. It was also observed that extrusion speed also significantly affects the parts quality and integrity [50]. Part deposition orientation during fabrication of ABS P43 was also examined with and without post chemical treatment and it was concluded that vapor treatment process reduces inaccuracy in part with chemical treatment [51]. Moreover, parts build with orientations either parallel or perpendicular with respect to the axis of a part was observed to have minimum dimensional deviation. Geng et al. [53] suggested that proper synchronization between printing speed with extrusion speed is required for stable dimensions of the printed samples. An established relationship of extrusion speed and filament diameter into the extrusion control algorithm is required for better accuracy. It was displayed that the objects made with higher printing temperatures have the poorest surface quality, which also results in the worst tolerances [56]. It was recommended that the speed at which printing is done turned out to be a more significant factor in keeping the weight consistent and ensuring the accurate dimensions of printed dosage forms compared to the temperature used for printing [58]. The use of reverse engineering and 3D scanning was investigated by Mora et al. to examine the dimensional accuracy of ABS parts [60]. Their findings indicated that FDM technology can produce high-quality parts, and chemical surface treatments can enhance smoothness. The study highlighted that this approach provides efficient, cost-effective, and detailed analysis of both small and large complex components, making it suitable for industrial applications.

A careful insight showed that there can be various causes of dimensional inaccuracy in FDM fabricated part. These can be due to shrinkage, lack of structural integrity and improper synchronization of printing parameters. However, the authors believed that use of optimum parameter setting for part fabrication can minimize these dimensional inaccuracies to great extent. Additionally, proper material selection, machine calibration, post processing operations in fabricated part can enhance the quality of fabricated part. The above-mentioned researches are some of the critical and highly cited FDM related researches conducted before 2020. Important researches related with the DA of the FDM part performed after 2019 is discussed in the next sub section.

3.2. FDM dimensional accuracy researches since 2020

In this section, DA related FDM researches published since 2020 are discussed. Figure 5 showed DA related FDM documents published country wise since 2020. Figure 5 presented that since 2020 the major countries contributing the FDM related DA studies are India, China, and Malaysia. Figure 6 displayed the DA related documents published platform wise.

Akbas et al. [61] experimentally and numerically examined the effect of the nozzle temperature and feed rates on the dimensions of the FDM printed PLA and ABS parts. They experienced that width of strip increase with rise in temperature for PLA samples whereas ABS samples showed mixed behavior. As a result, accuracy of PLA samples was better than ABS samples. They also noticed decrement in strip width with increasing feed rate for most cases. Despite their findings few discrepancies are observed at high feed rates and nozzle temperatures. Vyavahare et al. [62] conducted a study to analyze the impact of critical FDM parameters for the DA of FDM fabricated ABS parts. The part was complex having pyramidal and conical features. A regression model was proposed for the responses and key process parameters were optimized. It was suggested that the DA of fabricated parts depends on their dimensions. Additionally, they proposed that layer thickness, wall print speed, and build orientation are the most influential factors for the DA of FDM parts. Accuracy of expandable polystyrene (EPS) machined with 3D printed ABS tool was investigated by Sandhu et al. [63]. Using vertical milling machine linear grooves made on EPS was modified to perform the experiments. Experiments were conducted using the Taguchi L9 design and the effect of variation in process parameters on DA of the machined grooves was assessed. Mathematical models were developed and it was found that a strong correlation existed between the experimental result and predicted response by the developed model. Statistical analysis indicated that the DA was significantly affected by the depth-of-cut. The experimental results also demonstrate the possibility of using 3D printed ABS tools for machining soft polymeric materials in mass and batch production.

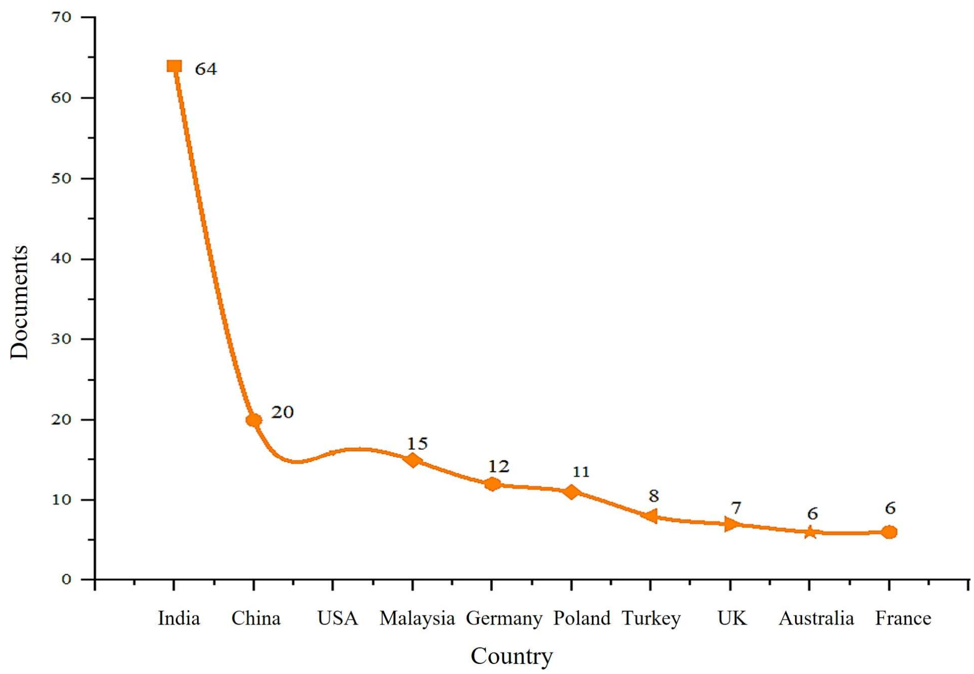


Figure 5. Dimensional accuracy related FDM documents published country wise since 2020 (source: Scopus).

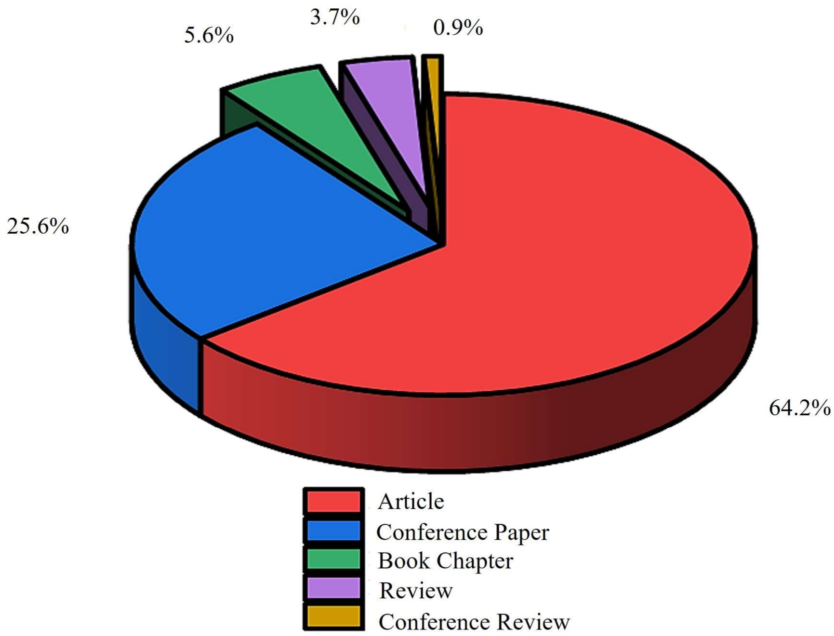


Figure 6. Dimensional accuracy related FDM documents platform wise published since 2020 (Source: Scopus).

Parametric optimization of FDM process and their impact on mechanical properties and part quality was reviewed by Sheoran and Kumar [64]. They observed that FDM process parameters like raster angle, orientation, layer thickness, build angle and raster width were more investigated and less attention was paid to other process parameters like interior infill pattern, infill density, temperature of extrusion, number of contours, etc. They also observed that statistical-based technique is more commonly used as optimization techniques and modern optimization methods like image processing, machine learning and deep learning require more application in optimization of AM processes. Negrete et al. [65] carried out experimental based research on optimizing FDM process parameters for improvement in part quality and process sustainability. It was observed that filling pattern was the key parameters affecting dimensional accuracy on inner and outer of the specimen. Desirability based optimization determined suitable value of layer thickness. Additionally, a sparse double dense filling pattern, and an orientation angle of 90° in the *XY* plane yielded the most favourable outcome. They also experienced their methodology improved the sustainability of the process without affecting productivity and part quality. Numerical modeling of the material deposition and contouring precision in FDM was investigated by Comminal et al. [66]. Flow of material extruded from FDM nozzle was simulated using the computation fluid dynamics method. The plastic material was modelled as an incompressible Newtonian fluid with a free surface. The simulated model dictates the appearance of road when the part was printed. To print a road four different strategies were used that has a sharp 90° turn. Different techniques were used like matching the speed of printing with how much materials are added, stopping at the turn sharply, or making the turn smooth and gradual. The computational fluid dynamics (CFD) simulation correctly plan the tool path and strategy for addition of material to improve the dimensional accuracy for FDM parts. Gao et al. [67] examined the influence of FDM parameters and filament quality on the structure and properties of polymer composite components used in automotive parts. Based on our experimental results, critical factors defining the DA of FDM parts were revealed. They outlined the performance criteria for FDM feedstock materials, considering their behavior during the feeding process. They proposed that this information serves as a guide for the advancement of novel polymer materials tailored to FDM technology. Finally, the desired mechanical properties and precise dimensions for FDM parts in the automotive industry was achieved by refining the printing process or enhancing the properties of the materials used. Maurya et al. [68] examined the prototype production of connecting rod using PLA plastic material in FDM. Investigation was done on the effect of process parameters on the DA, flatness and cylindricity. They used a regression model to predict DA, flatness, and cylindricity. They found that the best process parameters varied for each of the responses studied. Utility function revealed that best process parameters for the DA, flatness and cylindricity was layer thickness of 100 µm, linear infill pattern, inclined at 45º orientation, and 20 % infill density. To validate the results, a confirmation test was performed which revealed the results within the confidence interval defined. Mustafa et al. [69] investigated the performance of casting mating parts using different AM patterns for small batch production. They conducted a comparative study on FDM, Stereolithography, and Multi-Jet Fusion. Their research revealed that curing time is an important factor affecting DA and surface finish of the respective AM parts. Taczała et al. [70] compared the multi jet printing (MJP) with FDM in dentistry. The scans of the maxillary gypsum model were used to generate, primarily relying on the region with a missing left premolar. During experimentation, objects were positioned along the X and Y axes. The printed models were scanned and then overlaid onto scans of the plaster model using GOM Inspect V8 SR1 software. The researchers focused on the differences in space between the scans, and a map of deviations was created for each object to show these variances visually. The results revealed that average absolute value of deviations for FDM was 0.06 ± 0.04 mm in X axis and 0.07 ± 0.04 mm in Y axis. For MJP deviation in X and Y axis are 0.04 ± 0.02 mm and 0.06 ± 0.02 mm, respectively. A graph was also made to compare the average measurements of each tooth in the highest quality printouts from each series. It was observed that FDM printouts exhibited higher deviation values and thus MJP was suggested to create precise models due to its high accuracy. However, they proposed that, to enhance the dimensional accuracy and biocompatibility of FDM parts, larger number of measuring points should be considered in scans [70]. The authors agreed to the conclusion, as it is believed that high-resolution data allows a more precise assessment of dimensional deviations, which is crucial for ensuring that the part conforms to the exact specifications required in dental applications. Additionally, more measuring points provide a more comprehensive map of the part's surface which helps in identifying and addressing issues like warping, distortion, or irregularities that might not be captured with fewer points. The future aspect should focus on the application of accurate dimensional correction algorithms when more data points are available, leading to improvements in the final part's dimensional accuracy.

Gorgani et al. [71] explored a nonlinear error compensator for the dimensions of FDM-printed parts using a GMDH (Group Method of Data Handling) neural network. They focused on correcting dimensional errors regardless of their origin. Initially, they identified all parameters affecting the DA of the FDM process. The multi-input–single-output (MISO)data was then prepared using Taguchi design and collected results from 3D printed samples. They applied a GMDH neural network to utilize simple nonlinear regression formulas in each neuron and create complex neuron combinations, thus enabling analysis of small noisy data. To increase the efficiency, parameters of the network was optimized. A case study was also conducted which showed decrement in RMSE (Root mean square error) from 0.377 to 0.033 for nominal CAD model demonstrating the compensator's efficiency. A novel strategy of slicing to print overhangs parts without the requirement of support material was examined by Wuthrich et al. [72]. An algorithm was used along with geometrical transformation of the generated STL file. Further, slicing and back-transformation of the G-Code was also applied. Two reference parts were printed and analyzed. They found that a new slicing technique using cone-shaped layers worked effectively on the 4-axis printer. This enabled printing parts with 90° overhangs without requiring support material. They also observed that downward oriented surfaces and the upward oriented surfaces have same quality. They also proposed that printing parts with large overhangs is feasible. However, it was experienced that accuracy of the printed part was not as good as conventional 3D printer which used orthogonal kinematics. Chandrashekarappa et al. [73] used four different algorithms i.e., PSO, JAYA, RAO, and Bald eagle search (BES) to analyze and optimize the DA (in terms of cylindricity error) of high impact polystyrene material printed using FDM. Response surface-based methodology was used to design the experimentation and control variable affecting the dimensional deviation was analyzed. Analysis revealed that shell thickness and interaction of layer thickness with shell thickness and print speed significantly affected the cylindricity error. The model developed presented high regression value which showed the suitability of model in predicting the output response. Moreover, all four algorithms were utilized to identify the optimal FDM conditions across six case studies. It was observed that BES and RAO-3 algorithms were more efficient and determined optimal conditions at reduced computational time. Gómez-Gras et al. [74] performed experimental study to compare the accuracy of cylindrical printed parts with FDM and accuracy of holes machined using machining. The specimen selected was PEI Ultem 9085, and the comparison mainly emphasizes the value of roughness and tolerances. The study revealed the optimum combination of technological parameters both through machining and FDM technology which would produce comparable results. Mansaram et al. [75] investigated the DA of FDM fabricated ABS M30 parts. They experienced that the process parameters and their interaction govern the dimensions of the parts built in a varied direction, and the parameters are tuned to enhance the DA of the fabricated parts. They also suggested shrinkage of semi-molten material, which is extruded through nozzle lead to the dimensional inaccuracy and thus they have analyzed the dimensional inaccuracy in terms of volumetric deviation. Effect of extrusion temperature and slicing height on accuracy of FDM parts was also investigated by Syrlybayev et al. [76]. The part was first designed using a CAD software and then manufactured with different printing parameters to evaluate the DA. It was concluded that increase in extrusion temperature caused increased error along the axis normal to the printing plan. However, accuracy in X-Y plane was unaffected for the major features except the cylindrical holes, where shrinkage happened. Shrinkage also increased the separation of the outer shell from the infill. It was also observed that increase in layer thickness decreases printing accuracy in Z direction. To minimize the post treatment of parts in FDM, a new in situ foaming FDM technology was utilized to efficiently produce microcellular polyetherimide (PEI) honeycomb foams with different lattice structures [77]. A longer time printing ability and good printing performance was offered to CO_2-saturated PEI filament due to very low gas diffusivity. The printing process took up to 7 days, during which a microcellular structure was formed within the deposited foam strands. It was observed that PEI foams exhibit high DA for external regions with relative accuracy of 1.3%–6.4%. However, a low internal accuracy was observed in comparison, due to improved nozzle expansion and decrease in melt velocity. High accuracy control of microstructure, green processing, and log printing time offer the in-situ foaming FDM technology to exhibit better application scenarios for fabricating hierarchical cellular materials. Consequently, an accuracy correction based on nozzle expansion is suggested to improve the DA of the foam parts.

Learning-based error modeling in the FDM process was performed by Charalampous et al. [78] to develop a novel methodology for selection of process parameters to improve the DA. Regression-based machine learning algorithms were used to envisage the differences in size between the CAD model and the produced part. Initially, a simple model was created, and a database containing measurements of 3D printed parts was collected to create predictive models. Adjustments were made to the dimensions of the 3D model to address overall shape deviations and enhance process accuracy. To evaluate the efficacy of methodology in real-world manufacturing settings, a complex benchmark model and a freeform shape were fabricated using various scaling factors and different printing conditions. The developed regression models proved effective in recommending printing conditions and compensating for errors. Charalampous et al. [79] suggested use of vision based real time monitoring of extrusion AM processes for automatic error detection in manufacturing. The method established a correlation between the physical printed part and the digital CAD model measurements to measure the performance of the AM process. Precisely, detailed point cloud data of the AM part are collected, processed, separated, and reconstructed alongside the corresponding CAD model at different process stages. Finally, the effectiveness of the suggested automated monitoring and error detection approach is tested through experiments. It was experienced that the method efficiently captures and analyzes the geometric features of the manufactured AM component. The primary advantage of this method is its effectiveness, which remains consistent regardless of the complexity of geometry or the source of defects. Through this study, the authors want to suggest that, for enhancing the accuracy and efficiency of computer vision for evaluating FDM part accuracy, high-resolution imaging and advanced techniques in machine algorithm and artificial intelligence could be used for precise measurement. Ensuring rigorous calibration, alignment of the imaging system, and integration of 3D scanning could provide comprehensive analysis. Researchers should be encouraged to apply automated inspection systems for real-time monitoring and immediate feedback, coupled with data analytics for trend analysis and process optimization. Regular calibration with reference objects and continuous training with diverse datasets will further improve system accuracy and adaptability, thereby refining quality control in FDM manufacturing.

Optimization of DA of FDM printed part was done by Mohamed et al. [80]. They used definitive screening design (DSD) and deep learning feedforward artificial neural network (DF-ANN) methodology to estimate and forecast the impacts of crucial operating variables. They experienced that optimal conditions for cylindrical parts with better DA in less time was possible and even the number of complex experiments were reduced significantly. The deduced fabrication conditions were validated with the experimental measurement. It was observed that slice thickness, print direction, and number of perimeters considerably affected the percentage of length difference, whereas the percentage of the diameter difference was significantly affected by the raster air gap, bead width, number of perimeters, and part print direction. They suggested that DSD integrated ANN is a more promising method for application in AM. DA of 3D printed dental cast was performed by Park et al. [81]. A CAD reference cast was modified from a mandibular cast by addition of six cylinders in the canine, 2nd premolar, 2nd molar locations, and 3 spheres for establishing a coordinate system. FDM, digital light processing (DLP 1 and DLP 2), poly jetting, and stereolithography were used to cast 50 samples. Scanning of 3D printed casts was followed by superimposing them on CAD reference cast and deviations were measured to evaluate the overall consistency. For checking the DA, top co-ordinates of cylinders were extracted from each printed cast. Coordinates of the CAD reference cast was subtracted from the cast values to calculate the deviations in X, Y, and Z direction. Kruskal-Wallis test and the Mann-Whitney post hoc test were used for statistical analyses. It was observed that FDM printed casts showed more systemic deviations than all other process using superimposing analysis. FDM and DLP casts tended to contract whereas buccolingual expansion and expansion from front to back were observed for Polyjet and SLA casts. Prasong et al. [82] investigated on the improvement of interlayer adhesion of 3D printing of biodegradable blend composites. Composite filaments of binary and ternary blend were prepared. To improve the crystallinity of PLA, PBS (polybutylene succinate) was added to the blend composite. It was experienced that shrinkage behavior of molten PLA polymer during deposition was highly influenced by the degree of crystallinity, which cause reduction in the void area and increases the adhesion between layers, resulting in anisotropic characteristics and improvement to mechanical properties and heat resistance. However, large shrinkage volume when PBS is added to binary blend displayed poor surface quality and dimensional inaccuracy in addition to thermal distortion. They also observed that blending with PBAT (polybutylene adipate-co-terephthalate) provide ductility in the ternary blend composite, and thus, these composites showed good surface roughness and dimensional accuracy. Tao et al. [83] reviewed the effect of voids in FDM fabricate parts and provided in-depth discussions regarding feed wire and process parameters effect on void formation. They concluded that the presence of voids leads to inadequate layer-to-layer adhesion causing weaker part strength and anisotropic mechanical properties when compared to traditionally fabricated counterparts. Induction heating was applied in FDM part manufacturing by Oskolkov et al. [84] for better layer-to-layer adhesion quality, and homogeneity of material inside the complete printed part. For fast and consistent control of the material extrusion through the nozzle during printing, a specially designed testbed system was proposed. It features an ultra-lightweight induction-heated nozzle and a rapid temperature controller. This equipment allows for quick heating and cooling of the nozzle with minimal power input. However, nozzle with minimum thermal mass showed difficulty in uniform heat distribution on the nozzle surface. Multiphysics FEM model was used for deciding the inductor shape and thermal problem for nozzle and inductor. They also performed optimization of the inductor shape and signal frequency. Experiments were conducted at the optimized conditions, resulting in a prominent increase in heating speed and even distribution of heat on the nozzle surface. This enhances layer adhesion and improves the quality of the final part.

Wood or metal are generally preferred in traditional casting methods and pattern making through them is costly and time taking especially if the shape of pattern is thin and complex. To overcome these difficulties the use of FDM process was investigated by Ganganallimath et al. [85], where ABS part was used as a pattern material for quality improvement of sand castings. It was found that the use of ABS part in casting provide improved life, better yield, chemical resistance, surface finish and high dimensional accuracy even for precise geometrical shapes. The overall cost and lead time is also reduced increasing the casting efficiency. It was therefore suggested that combination of FDM and ABS part as input pattern material would help the casting industries to face present challenges. To overcome the problem related to cost and low batch size production, feasibility of FDM printed mandrels was tested towards electroforming of copper net-shape parts by Zheng et al. [86]. To enhance the geometric accuracy of deposition on the mandrel, an algorithm was proposed and it was found that desired net shape was achieved by correcting mandrel, that considered electrodeposition as important variable. They proposed that in applications where the DA of the outer shape is important, efforts should focus solely on enhancing the accuracy of the outer surface, while achieving uniform part thickness is of lesser significance. They suggested a new method to make parts with different thicknesses on one mold. They also showed that it could be used to make high aspect ratio flexures.

They finally found that electroforming offered greater design flexibility and structural control compared to the FDM process, which could potentially serve as an alternative solution for producing small batches and complex assemblies using tall mandrels. Sensitivity of FDM printed material to moisture was identified with a fast test performed by Hamrol et al. [87]. The experiment was set up to study the effect of moisture on the FDM process, with a focus on a limited number of trials. Using a case study, they explored the influence of material temperature, layer thickness, extrusion rate, and material flow on the DA. They experienced that by proper adjustment of these factors, optimal parameters could be identified. The results showed a notable increase in sample dimensions at a filament moisture content of 0.74% and surface quality degradation at specific humidity levels. However, moisture did not seem to have a significant impact on the mechanical strength of the FDM samples. Dimensional and geometrical performance assessment of two FDM printers (Ultimaker S3 and Intamsys FUNMAT HT) using a benchmark artifact design was carried out by Spitaels et al. [88]. Each printer fabricated five ABS parts, while the Ultimaker S3 produced five PLA parts, showing effect of material choice on dimensional and geometric performance. Tolerance intervals (IT) were determined using the ISO method, revealing between IT 10 and IT 15 depending on feature size for both printers. The highest deviation was in coaxiality, with average values ranging from 0.376 to 0.679 mm for Ultimaker S3 in PLA and ABS, and 0.759 mm for FUNMAT in ABS. FUNMAT HT showed better IT consistency along X and Y axes but lower performance in the Z axis compared to Ultimaker S3. It also struggled more with reproducing features along the Z axis. However, the Intamsys printer demonstrated more accurate repetition of other geometric features. Hira et al. [89] analyzed the best shape and manufacturing settings for FDM process nozzles, using both numerical simulations and experiments. FDM samples were printed and measured using image processing. A linear regression model was built from experimental data to study manufacturing effects. This model was validated against experimental results to find the best nozzle geometry. Nozzles with optimal geometry were made and samples are compared. ABS samples exhibited more swelling than PLA and CPE. Feed rate, temperature, and measurement position affected strip widths, but optimal nozzle geometry minimized these variations. It was thus inferred that DA of FDM printed parts can be improved using optimized nozzles. DA of medical models of the skull produced by FDM technique by advanced morphometric analysis was shown by Aristotle et al. [90]. Human anatomical skulls were CT (computed tomography) scanned, and the digital imaging and communications in medicine files were converted to STL format by MIMICS v10.0 software. The skull was then printed using FDM technology having 0.05 mm resolution and using PLA filament of o.4 mm diameter. The accuracy was assessed by comparison of the morphometric parameters in the FDM-printed skull with that of original human skull and with CT images to validate the precision of the printed skull. ANOVA analysis for all 3 groups exhibited that the 3D skull models were highly accurate, reliable and minimal dimensional error was experienced between all groups. They concluded that FDM can be used to obtain accurate and reliable anatomical models with negligible dimensional error and the models were highly reproducible. Modeling and investigation were done for development of correction factors for FDM printer [91]. The study examined the impact of part orientation and various printer models on the production of highly precise parts using FDM. ABS and PLA, typical printing materials, were employed, along with two different FDM printers, to evaluate the effects of hardware disparities. Examining the collected data showed a substantial scattering of measured results leading to difficulty in the application of correction factors. ANN algorithm was also presented to predict the outcome of future prints. The developed ANN model proved accurate and dependable in determining a processing window, printing parameters, and correction factors essential for optimizing the FDM process to produce high-precision parts. Nugroho et al. [92] investigated the DA of FDM-printed polyurethane (PU) dog-bone samples considering thickness, grip section width, full length, circularity, and cylindricity. The researchers analyzed the effect of nozzle temperature, infill percentage, print speed, and layer height effect on the DA. Testing various combinations of these parameters provided an optimal setting for achieving the best DA. A confirmation study was also conducted to ensure that the experimental results could be reproduced reliably. It was concluded that layer height was the most significant parameter affecting the DA, whereas infill density has no significant effect on all sample dimensions. Frunzaverde et al. [93] examined the effect of the printing temperature and the filament color on the DA of FDM-Printed PLA samples. Two types of PLA filament were used in the study: (1) Verbatim PLA Filament of diameter 1.75 mm natural; and (2) Verbatim PLA Filament of same diameter (1.75 mm) but black in color. Based on the earlier researches the printing temperature (200–240 °C) was the only process parameter selected for investigation. Experimental study clearly demonstrated that DA of the sample varies with polymer color under the same condition. It was therefore, recommended that process parameter optimization for FDM process should always consider the proper selection of PLA material in terms of color as well as fabricant. To deeply understand how filament color and moisture content affect the DA of FDM parts and propose effective solutions, further research could focus on several key areas. Few of them are: (1) Investigating the effect of different colors on the thermal properties of filaments, such as heat absorption and dissipation. This can influence how colors impact extrusion behavior and layer bonding; (2) Printing test parts with various colors and moisture levels and analyzing the deviations from the intended dimensions; (3) Explore effective methods for storing filaments to minimize moisture absorption. Developing improved filament packaging or storage systems that are more effective at keeping filaments dry; and (4) Developing predictive models and simulations to better understand the effect of color and moisture content on printing outcomes. This includes creating models that can simulate how different filament properties influence print quality.

Lluch-Cerezo et al. [94] examined the effect of annealing temperatures on powder mould effectiveness to avoid deformations in ABS and PLA samples. Variation in length, width and height of specimen and mould usage effectiveness during the annealing process at different temperatures were evaluated. As length of the part is primarily affected by deformation thus length of the part was mainly focused to evaluate the specimen accuracy. A polynomial approximation was done to predict the effectiveness of mould and deformation’s length. The results demonstrated that mold effectiveness increases with annealing post processing temperature. It was further experienced that, PLA being semi-crystalline thermoplastic showed lower deformation due to a lower shrinkage during thermal post-processing. ABS, being amorphous, showed higher deformation. Zuo et al. [95] also claimed that poor layer adhesion between FDM part affects its quality. To overcome this challenge a new print-healing methodology was proposed. A polymer ink (Cu-DOU-CPU) was developed with synergistic triple dynamic bonds which imparts exceptional printing ability and self-healing ability at room-temperature. A compact printer was used and objects with different shapes were printed and assembles into large structure via self-healing. Due to triple dynamic bonds, strong adhesion between layer was obtained. In addition, spontaneous healing of damaged printed objects significantly improves their service life.

Quality assurance in 3D printing was performed by examining patient-specific vascular anatomical models made using digital anatomical segmentation and various 3D printing methods (FDM, SLA, SLS, and PolyJet) [96]. The results showed that printing processes consistently produced high-quality handheld patient-specific models. When compared to unmodified CT Angiograms (CTAs), the overall dimensional errors were within 0.20 ± 3.23% for FDM, 0.53 ± 3.16% for SLA, −0.11 ± 2.81% for PolyJet, and −0.72 ± 2.72% for SLS printed models. Comparing the 3D models to CTA data, the average relative dimensional error was −0.83 ± 2.13% obtained from digital anatomical segmentation and processing. The dimensional errors from the prints alone were within 0.76 ± 2.88% for FDM, +0.90 ± 2.26% for SLA, +1.62 ± 2.20% for PolyJet, and +0.88 ± 1.97% for SLS printed models. The study concludes that 3D-printed patient-specific vascular anatomical models exhibit a high level of DA and recommends their use in clinical applications for medical devices. Dimensional behavior of FDM fabricated materials (PLA and PLA-X) using 3D scanning was examined by Golubovic et al. [97]. 3D scanning of the samples was carried out after part fabrication and after one week of part fabrication to determine the changes in dimensions of fabricated model. A graph was then plotted between scanned data recorded on different days of the week. Inconsistencies in the model of the scanned surface showed minor error along the length and width of specimen. A decreasing trend was observed in the length of the specimen. Due to the incomplete scanned models, the peaks were more noticeable in the PLA-X samples whereas for PLA samples, the stabilization of the geometry was recorded on fifth day. It was then recommended that dimensional control should be performed after a week to optimize the process. Predictive modeling of out of plane deviation for the quality improvement in FDM fabricated samples was performed by the Wang et al. [98]. To quantify the deviations in *X*, *Y* and *Z* direction, they have established a 3D printing scanning setup which collect the 3D point cloud data of the FDM fabricated part and compare them with nominal 3D point cloud data. Their work was more focused in predicting the estimated deviation along the Z-direction using a deep learning-based prediction model. To validate their methodology a FDM printed prototype of human knee was used to conduct the experimentations and to show the effectiveness of the proposed methods. Investigation on the effects of air controller unit on the DA of porous structures manufactured using FDM was performed by Emir et al. [99]. Gyroid and BCC porous structures were fabricated in AC and non-AC environment. An average of 2% deviation in terms of dimensions was recorded on part produced in AC environment whereas 2.5% dimensional deviations was observed in non-AC environment. We believe that to optimize the manufacturing process of porous structures printed by FDM for improved dimensional accuracy special attention is required in selection of high-quality, biocompatible materials with predictable properties. Tuning of printing parameters is required to ensures precise control over the porous features. Use of advanced slicing software can enhance feature placement and density, while regular calibration of the 3D printer maintains accuracy. Utilizing optimal support structures prevents deformation, and post-processing techniques, such as annealing, improve mechanical properties and stability.

Fiedler et al. [100] checked the feasibility of robot-assisted processes for automated tolerance compensation of parts made using FDM technique. A prototype built for dimensional tolerance compensation was developed to analyze a flexible compensation method for dimensionally inaccurate parts made using injection moulding. KUKA robot was used to increase freedom of movements as compared to cartesian system. DA of the FDM fabricated samples and production time was evaluated and selected process modifications are used to further optimize the DA and production time. A line scanner was used to evaluate and assess the fabricated samples and result suggested that process can be made more accurate and cost effective. 3D biomimetic scaffolds act as a base for defect improvement while consequently developing extracellular matrix and bone regeneration and its DA is less studied. To address the same, DA of 3D biomimetic scaffold was examined by Gade and

Vagge [101]. A Taguchi full factorial design of the experiment was used for experimental design, and DA was considered response. Tuning of process parameters were done for PLA samples fabricated by FDM. Differential scanning calorimetry (DSC) and X-ray diffraction were used to assess the crystallinity of the PLA filament. A thermogravimetric analyzer was also used to investigate the thermal breakdown of filament material. The optimized DA was achieved at 0.14 mm of layer thickness, 20 mm/s of printing speed and 80 % of infill percentage. The result is further validated with response surface methodology result. Compensation of the shrinkage behavior in FDM fabricated components was examined by Koers and Magyar [102]. They attempted to counter act the dimensional deviation on the FDM fabricated samples using an in-house developed software and considering global as well as local shrinkage factors. They predicted the expected shrinkage within a layer using the developed software and verified it with experimental study performed on cylindrical FDM test samples. By doing so they detected an error and termed it as clover effect as a result of the shrinkage. It was observed that deposited layer is deformed by the distortion in the x–y plane comparable to a clover. A demonstrator in the form of bracket was finally analyzed for validation of the result. Computer vision-based evaluation of DA for material extrusion-based AM (MEAM) for developing new product was performed by Tu et al. [103]. They proposed a cheap and accurate computer vision-based framework for MEAM based on a single mobile phone camera with no fixed installation requirements. To minimize the influence of lens distortion the camera was calibrated and dimensions are measured through scaling and projective transformation. Checkerboard, symmetric circle and asymmetric circle were used to obtain the best calibration pattern. The proposed framework was then experimentally validated by printing test samples of cube and cylinder using FDM process. It was observed that asymmetric circular grid pattern showed the highest accuracy with 0.27% relative error of measured diameter for printed cylinder and relative error in length for printed cube was 0.65%. Additionally, the proposed framework displayed relative error of less than 1%. Mohanavel et al. [104] examined the impact of carbon nanotube addition on the DA of PLA nano composite fabricated by FDM. An innovative PLA nano composite was created by mixing PLA with 0, 1, 1.5, and 2 wt% using twin extrusion-based method. After the successful nanocomposite fabrication effect of varying concentration of nanotube addition was investigated on DA of FDM part. It was observed that variation in volumetric dimensions decreased with an increase in the carbon nanotube content and it was recommended that in PLA + 2 wt% carbon nanotubes error decreased by 50% when compared with pure PLA polymer matrix under the same processing conditions. Accuracy of FDM processed parts based on tolerance-fit system was explored by Grgic et al. [105]. A novel CAD method based on clearance fit was used. In addition, ISO system and systematic calibration procedure of 3D printer was used to achieve the better DA of the parts. For selecting best hardware and software features, the systematic examination of CAD Slicing software and 3D printer interaction was performed. For part joining into a clearance fit, measure of roundness tolerance was also provided and shaft tolerance ranges in the hole base system was determined. They showed that horizontal expansion parameter and hole horizontal expansion parameter should be 0 and 0.13 mm, respectively. Additionally, the linear advance factor of 25 was recommended. The result proved that FDM can produce parts within the permissible limits for the tolerance, fit and type of clearance fit. They proposed that their approach can solve inaccuracy problem in product manufacturing and the limitation of work volume in low cost FDM printer can also be solved which increases their use in the product development and manufacturing process. Few other important studies can also be found in [106–110].

3.2.1. Studies showing experimental results of DA in FDM

Hanon et al. [111] investigated the accuracy of 3D printed PLA parts printed with different process parameters and colors. Worst dimensional accuracy with elevated standard deviation error was observed in the 45° angle specimens (Figure 7). It was due to the layers positioning, as layers of this specimen were built tilted. The possibility of distortion increases due to the influence of gravity throughout curing. Agarwal et al. [112] analyzed the impact of printing parameters on ABS specimen printed by FDM. Based on their outcome, surface plot between the two most significant process parameters i.e., layer thickness and print speed is shown in Figure 8. A linear increase in dimensional deviation was observed with increase in layer thickness whereas, a non-linear relationship was recorded with rise in print speed. They observed that at maximum layer thickness and slowest print speed results max deviation of 9.07% was observed whereas highest print speed and lowest layer thickness yielded the least deviation of 2.8% in the part. Tiwaria et al. [113] made five slots each having different orientation and observed the variation in error % with various slot angles. The result displayed that error % decreases with the increase in slot angle and the lowest error was recorded at 90º (Figure 9). Kim and Ko [114] displayed that the dimensional accuracy of an object can be determined based on the dimensional errors in the x-and y-axes (Figure 10).

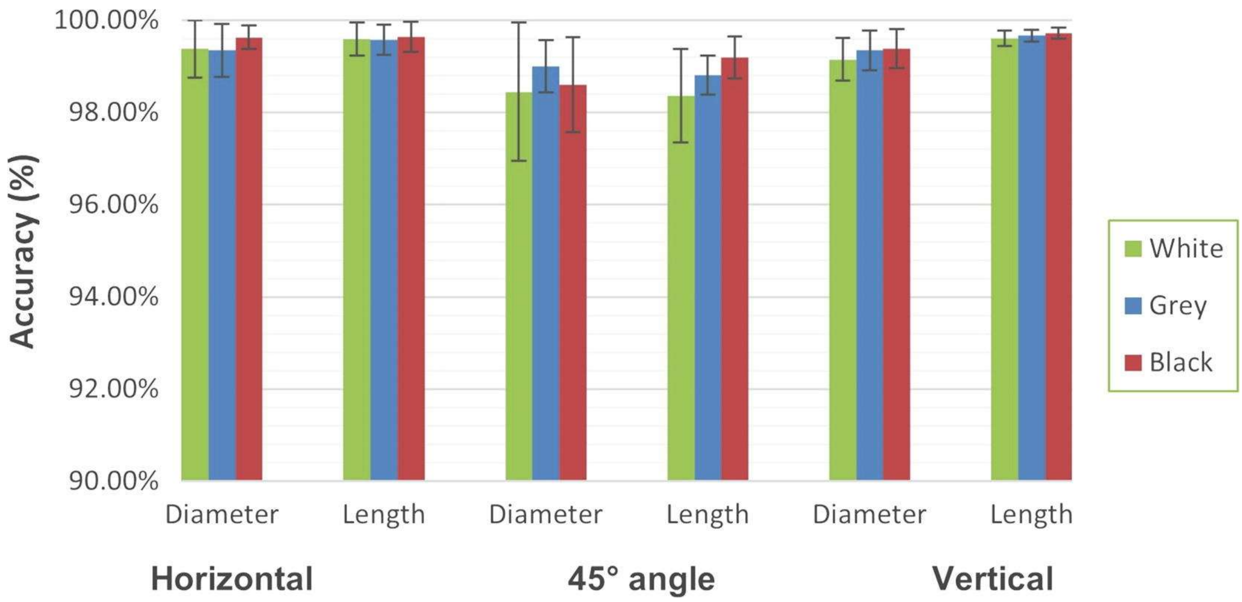


Figure 7. Dimensional accuracy result showed by Hanon et al. [111].

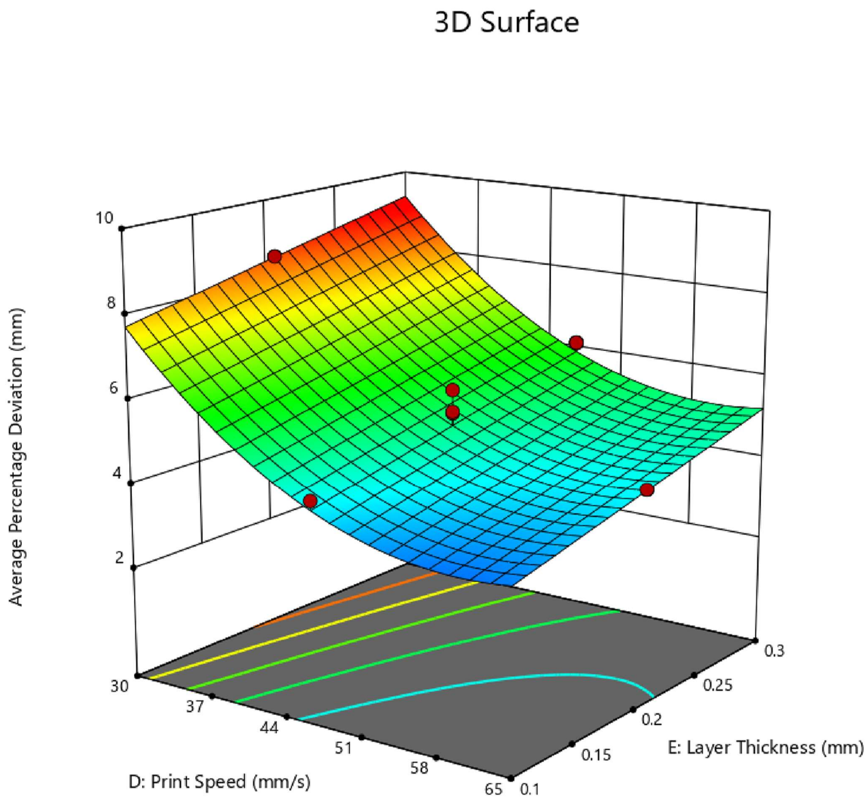


Figure 8. Impact of printing parameters on ABS specimen printed by FDM [112]

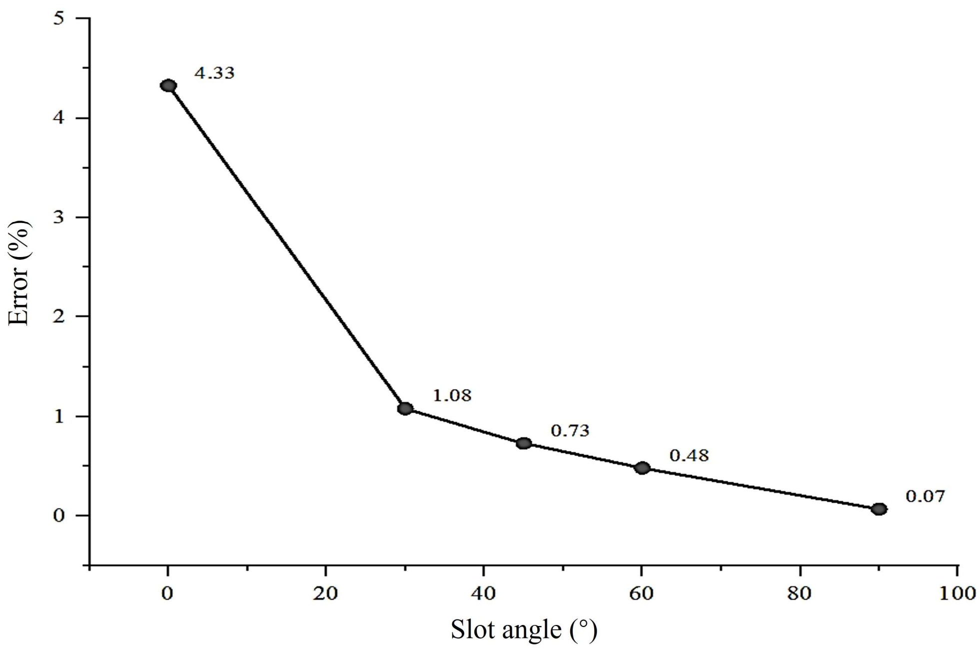


Figure 9. Variation in error % with various slot angles [113].

To ensure that readers can easily grasp the key points, Table 3 provides a summary of critical findings from few highly cited studies published after 2019. It's important to note that Table 3 does not cover every paper reviewed in sections 3.2 and 3.2.1. Instead, it highlights selected research to give readers a clearer view of the most impactful discoveries in the field. This approach streamlines the information by concentrating on major contributions, while noting that a comprehensive review of all the discussed papers can be found in the aforementioned sections.

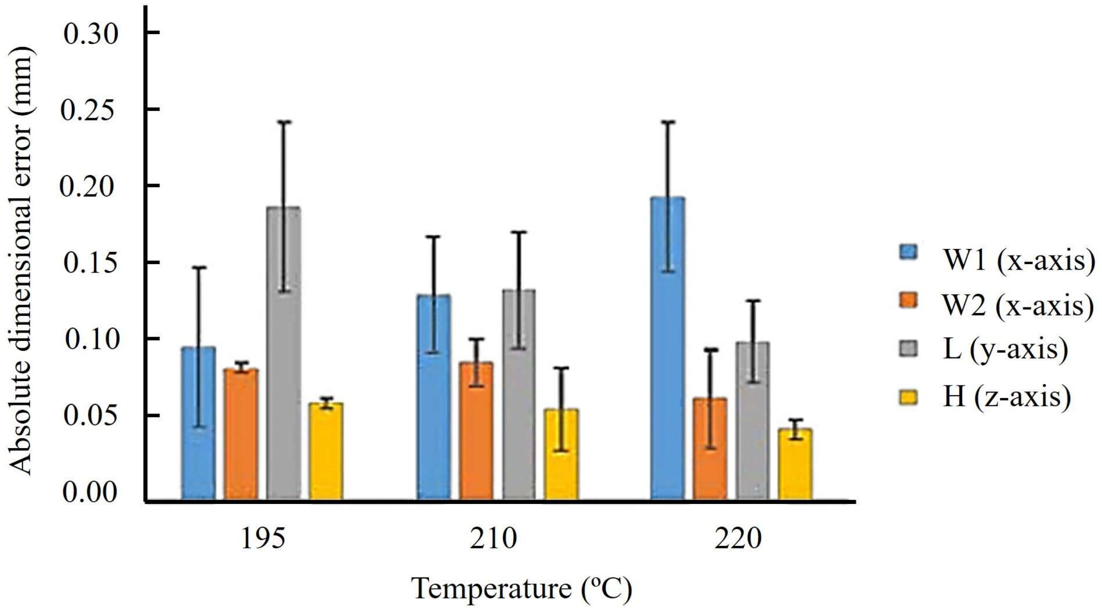


Figure 10. Dimensional result obtained by Kim and Ko [114].

Table 3. Discussions of critical dimensional studies researches conducted since 2020.

Ref.	Investigation	Findings
Akbas et al. [61]	Experimental and numerical analyses investigated the impact of variations in nozzle temperature and feed rates on the dimensions of PLA and ABS parts printed using FDM technology.	It was experienced that with rise in temperature, unlike ABS, width of PLA strips increases. PLA parts were more accurate than ABS. Higher feed rates made strips narrower most of the time. As expected, they find some differences at high feed rates and temperatures.
Sandhu et al. [63]	Investigated the accuracy of expandable polystyrene (EPS) machined with 3D printed ABS tool.	DA was significantly affected by the depth-of-cut. The experimental results revealed that use of 3D printed ABS tools for machining soft polymeric materials in large-scale and batch production is feasible.
Negrete et al. [65]	Experimental based research on optimizing FDM process parameters for improvement in part quality and process sustainability.	Filling pattern was the key parameters affecting dimensional accuracy on inner and outer of the specimen. They also experienced their methodology improved the sustainability of the process without affecting productivity and part quality.

Continued on next page

Ref.	Investigation	Findings
Comminal et al. [66]	Numerical modeling of the material deposition and contouring precision in FDM was investigated.	The FDM material flow from FDM nozzle was simulated using CFD. This simulation predicted how the printed part's layers would look, especially when printing roads with sharp 90° turns. Four strategies were tested, including adjusting printing speed to match material addition, sharp stops at turns, or gradual turns. The CFD simulation accurately planned tool paths and material addition strategies, enhancing dimensional accuracy for FDM parts.
Mustafa et al. [69]	Investigated the performance of casting mating parts based on different AM patterns for small batches.	A comparative study on FDM, Stereolithography and Multi-Jet Fusion was performed. The finding of the research revealed that curing time is a significant parameter for DA and surface finish of respective AM parts.
Taczała et al. [70]	They explored the comparison between multi jet printing (MJP) and FDM technology in dentistry.	During the experiment, objects were placed along the *X* and *Y* axes. The printed models were scanned and overlaid onto scans of the plaster model using GOM Inspect V8 SR1 software. A graph was made to compare the average measurements of each tooth in the best printouts from each series. FDM printouts shown higher deviation values. Additionally, models printed along the *X*-axis showed smaller deviations compared to those printed along the *Y*-axis.
Gorgani et al. [71]	Investigation was performed on a nonlinear error compensator for dimensions of FDM printed part using a GMDH neural network.	To enhance efficiency, the network parameters were optimized. A case study was conducted, demonstrating a decrease in RMSE for the nominal CAD model, showcasing the effectiveness of the compensator.
Wuthrich et al. [72]	A novel strategy of slicing to print overhangs parts without the requirement of support material was investigated.	They experienced the novel slicing method employing cone-shaped layers showed effective on the 4-axis printer, enabling the printing of parts with 90° overhangs without support material. Downward and upward oriented surfaces exhibited similar quality. It was suggested that printing parts with significant overhangs is achievable. However, it was observed that the accuracy of the printed parts was not on par with conventional 3D printers.
Zhai et al. [77]	A novel in situ foaming FDM technology was used to proficiently manufacture the microcellular polyetherimide (PEI) honeycomb foams with various lattice structures.	It was observed that PEI foams exhibit high DA for external regions with relative accuracy. When compared to conventional methods, lower internal accuracy was noticed due to increased nozzle expansion and reduced melt velocity. Nevertheless, precise control over microstructure, efficient green processing, and shorter printing times makes in-situ foaming FDM technology more suitable for producing hierarchical cellular materials in various application scenarios.

Continued on next page

Ref.	Investigation	Findings
Charalampous et al. [78]	A new approach was developed through learning-based error modeling in the FDM process to enhance dimensional accuracy by selecting optimal process parameters.	It was experienced that regressive models developed can be effectively used for recommending printing conditions and error compensation.
Prasong et al. [82]	Investigated on the improvement of interlayer adhesion of 3D printing of biodegradable blend composites	They also observed that blending with PBAT provide ductility in the ternary blend composite and thus the ternary blend composites showed good surface roughness and dimensional accuracy.
Tao et al. [83]	Investigated the effect of voids in FDM fabricate parts and presented a detailed discussions on the effects of feed wire and process parameters on void formation.	They concluded that presence of voids leads to inadequate layer-to-layer adhesion causing weaker part strength and anisotropic mechanical properties when compared to traditionally fabricated counterparts.
Ganganallimath et al. [85]	Investigated the use of ABS part as a pattern material for quality improvement of sand castings	They experienced that use of ABS part in casting provide improved life, better yield, chemical resistance, surface finish and high dimensional accuracy for precise geometrical shapes. The overall cost and lead time is also reduced increasing the casting efficiency.
Zheng et al. [86]	Feasibility of FDM printed mandrels was tested towards electroforming of copper net-shape parts.	In conclusion, the FDM process exhibited significant advantages in terms of design flexibility and structural control when compared to electroforming. This makes it a potential alternative solution for low batch production and the fabrication of complex assemblies, especially those involving mandrels with high aspect ratios.
Hamrol et al. [87]	Sensitivity of FDM printed material to moisture was identified with a fast test.	The test suggested that a significant increase in dimensions of produced samples was recorded when filament moisture content level is 0.74%.
Aristotle et al. [90]	DA of medical models of the skull produced by FDM technique by advanced morphometric analysis was investigated.	The 3D skull models displayed high accuracy and reliability, with minimal dimensional errors observed across all groups. The researchers concluded that FDM is suitable for producing anatomical models with precision and reliability, showcasing negligible dimensional errors and high reproducibility.
Frunzaverde et al. [93]	Investigation on the effect of the printing temperature and the filament color on the DA of FDM-Printed PLA samples was made.	The experiment showed that the appearance of the sample changes depending on the color of the thermoplastic used, even if everything else remains the same. So, it was suggested that when adjusting the settings for FDM, it's important to choose the right color of PLA plastic from the right manufacturer.
Zuo et al. [95]	A new print-healing methodology was proposed.	A special polymer ink called Cu-DOU-CPU was created. It has three types of bonds that work together, making it great for printing and able to heal itself at room temperature. It was observed that spontaneous healing of damaged printed objects significantly improves their service life.

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Ref.	Investigation	Findings
Nguyen et al. [96]	A study of patient-specific 3D-printed vascular anatomical models fabricated using digital anatomical segmentation and FDM, SLA, SLS and PolyJet 3D printing respectively.	The research revealed that 3D-printed models of blood vessels made for individual patients have a lot of detail and accuracy. It suggests that these models can be used in medical tools for treating patients.
Emir et al. [99]	Investigation on the effects of air controller unit on the DA of porous structures manufactured using FDM was performed.	Parts made in an air-conditioned room had around a 2% difference in size compared to parts made in without air conditioning where, difference was about 2.5%.
Fiedler et al. [100]	Feasibility of robot-assisted processes for automated tolerance compensation of parts made using FDM technique was examined.	The DA of the samples produced via FDM and the time taken for production were assessed. Subsequently, specific adjustments were implemented to further enhance both the DA and production efficiency. Utilizing a line scanner, the fabricated samples were meticulously evaluated, revealing opportunities for refining the process to achieve greater precision and cost-effectiveness.
Gade and Vagge [101]	DA of 3D biomimetic scaffold was examined.	DSC and XRD techniques were employed to analyze the crystalline structure of the PLA filament. A thermogravimetric analyzer was also used to examine the thermal decomposition behavior of the filament material. Through experimentation, the optimal DA was attained at a layer thickness of 0.14 mm, a printing speed of 20 mm/s, and an infill percentage of 80%.
Koers and Magyar [102]	Compensation of the shrinkage behavior in FDM fabricated components was examined.	The observation indicated that the deposited layer experienced deformation in the x-y plane akin to the shape of a cloverleaf. Subsequently, a bracket demonstrator was subjected to thorough analysis to validate these findings.
Tu et al. [103]	Computer vision-based evaluation of DA for material extrusion-based AM for developing new product was performed	The examination revealed that the asymmetric circular grid pattern exhibited the highest level of accuracy, with a relative error of 0.27% in the measured diameter for the printed cylinder and a relative error of 0.65% in the measured length for the printed cube. Furthermore, the suggested framework demonstrated a relative error of less than 1%.

4. Discussion

A review of 3D printing process namely FDM and its advancement in dimensional accuracy is reflected in the present research. Although there are number of related researches available in literature but special attention is paid to the paper published after 2019. For the awareness of reader, a section namely section 3.1 presented findings of the some of the highly cited researches published before 2020. However, since a review study showing an advancement in dimensional measurement for the studies conducted after 2019 is limited, a review study is required that highlights the important findings of research papers published from 2020–2024. The review presents a critical insight on latest development in dimensional studies of the FDM and reflects that several new factors that affect the dimensional accuracy of FDM parts have been discovered, reflecting the novelty in the review study performed. Additionally, it can be observed that the application of FDM part is not limited only to manufacturing industries or mechanical components. FDM parts also finds wide applications in healthcare sector like dentistry, anatomical models and tissue engineering [81,90,101]. The significant findings of the some of the highly cited reviews presented in the current study are summarized in the bullet points below:

- Shrinkage during FDM part fabrication is the main reason for parts inaccuracy [48]. Additionally, other process parameters like infill pattern, rater angle, raster width, air gap, build orientation, etc. also influenced the part geometry and its accuracy. It is strongly recommended to operate machine at optimum factor setting for minimizing the dimensional inaccuracy.
- Proper synchronization between printing speed with extrusion speed is primarily required for stable dimensions of the printed samples.
- Products fabricated at elevated printing temperatures exhibit inferior surface quality, leading to worst tolerances.
- Vapor treatment process is also recommended to minimize the variations in part geometrical accuracy.
- Curing time is another significant parameter for DA and surface finish of respective AM parts.
- Presence of voids leads to inadequate layer-to-layer adhesion causing weaker part strength and anisotropic mechanical properties when compared to traditionally fabricated counterparts.
- To enhance the dimensional accuracy and biocompatibility of FDM parts in the medical field, larger number of measuring points should be considered in scans [70].
- Use of vision based real time monitoring of extrusion AM processes is recommended for automatic error detection in manufacturing [79].
- Dimensional accuracy of FDM samples was also influenced by moisture content in the filaments used for part fabrication. Research [87] showed that a significant increase in dimensions of produced samples was recorded when filament moisture content level is 0.74%.
- FDM is suitable for producing anatomical models with precision and reliability, showcasing negligible dimensional errors and high reproducibility [90].
- Filament color is pointed as another important factor that affect the dimensional accuracy of FDM parts [93]. Deep understanding on how filament color and moisture content affect the DA of FDM parts is presented and effective solutions are proposed in this study.
- Investigation on the effects of air controller unit on the DA of porous structures manufactured using FDM showed that parts fabricated in AC room is more dimensionally accurate than non-air-controlled environment [99].
- The use of asymmetric circular grid pattern exhibited the highest level of accuracy, with a controlled relative error [103].

5. Conclusions and challenges

The research presented a review study on the dimensional accuracy of FDM process. To make the study more effective, all the research papers presented in this study is collected from Scopus and web of science database. Although some of the critical researches performed before 2020 were presented but the aim was to present the findings of FDM related dimensional studies conducted since 2020. A bibliometric analysis was given to enhance the scholarly depth and methodological robustness of the review.

FDM is a material extrusion process, the material is heated in the extruder and then deposited in the build platform. Shrinkage is found to be the most significant parameter affecting the accuracy of fabricated parts especially along the length and the width of the part. The review also shows that the dimensional accuracy is mainly affected by the chosen process parameters like raster angle, build orientation, air gap, infill pattern, etc. Additionally, extrusion temperature, and printing speed also influenced the dimensional behavior of FDM samples. The results also revealed that dimensional accuracy of FDM samples is not only affected by the chosen process parameters, in addition, filament color, and moisture content of the used filament also influenced the dimensional accuracy of the FDM parts. It can be also experienced from the study that using FDM is not only limited to finite areas. FDM parts are widely used in casting, electronics, medical, healthcare, and other applications.

There are several challenges in maintaining the précised dimensional accuracy of FDM parts. However, controlling the part shrinkage after fabrication is the primary challenge. In addition, another critical parameter in the challenges of maintaining dimensional accuracy in FDM is the layer height. The layer height directly influences the surface finish and dimensional precision of printed parts. Larger layer heights can lead to visible layer lines and reduced accuracy, while smaller layer heights require longer print times and may be more susceptible to issues such as nozzle clogging or poor adhesion between layers. Balancing layer height with print speed and material flow rate is essential for achieving accurate dimensions in FDM printing. Some of the other challenges to be controlled are:

1. Temperature control: precise control of nozzle and build plate temperatures is crucial. Moreover, variations in temperature can lead to material shrinkage or warping, impacting dimensional accuracy.

2. Material properties: different filaments have varying thermal expansion coefficients and mechanical properties. Thus, understanding these properties and how they interact with the printing process is essential for achieving accurate dimensions.

3. Build plate adhesion: ensuring proper adhesion between the printed object and the build plate is critical. Thus, poor adhesion can result in part detachment or shifting during printing, leading to dimensional inaccuracies.

4. Overhangs and support structures: printing overhangs without proper support structures can cause drooping or sagging, affecting the overall geometry and dimensions of the object.

5. Extrusion consistency: inconsistent extrusion of filaments can lead to variations in layer thickness and uneven deposition, impacting dimensional accuracy.

6. Future research recommendation

A careful insight on the presented review highlighted the various causes of dimensional inaccuracy in FDM fabricated part. These can be due to shrinkage, lack of structural integrity and higher liquidity and gravity material flow. However, we believe that using optimum parameter settings for part fabrication can minimize these dimensional inaccuracies. A statistical multi-response optimization like grey relational analysis (GRA) integrated with the Taguchi method, principal component analysis and others can be used for process optimization. Additionally, researchers are encouraged to use advanced machine learning techniques and artificial intelligence techniques for ensuring the quality of the printed part.

• Future research on enhancing DA in FDM technology should concentrate on several pivotal areas. Research should be focused on the development of advanced materials with superior thermal stability, reduced shrinkage, and improved mechanical properties to address current accuracy limitations.

• Advancement in precision engineering, including refined nozzle designs and enhanced temperature control systems, are crucial for minimizing deviations during printing.

• Real-time monitoring and feedback mechanisms employing sensors and machine learning algorithms should be encouraged to enable adaptive adjustments and maintain precision throughout the printing process.

• Improvements in slicing and simulation software to better predict and compensate for material-specific behaviors will enhance accuracy.

• Standardization of testing protocols and benchmarks for accuracy will facilitate consistent evaluation and improvement.

• Combining FDM with other manufacturing methods, like additive and subtractive processes, can improve precision and expand its applications.

For the better understanding of the work, a SWOT analysis is presented below, which enables researchers and readers to effectively understand the strength, weakness, opportunities, and threats of the research.

1. Strength

(1) Regular calibration of the printer.
(2) Properly set the nozzle height to prevent over-extrusion or under-extrusion.
(3) Use an enclosed chamber to maintain consistent ambient temperatures, reducing thermal fluctuations.
(4) Use high-quality, consistent-diameter filaments to reduce variability in extrusion.
(5) Use software that enables dimensional compensation to account for any known inaccuracies.

2. Weakness

(1) Inconsistent heating of the nozzle or print bed.
(2) Non-uniform cooling, especially in materials that shrink significantly as they cool.
(3) Inconsistent filament diameter or quality can affect extrusion rates, leading to uneven layers.
(4) Poorly designed or insufficient supports can lead to sagging or collapsing during printing.
(5) Non-uniform shrinkage in different directions.

3. Opportunities

(1) Implement automatic calibration systems to ensure consistent alignment of the axes and nozzle height.
(2) Upgrade to higher-resolution stepper motors to improve positioning accuracy.
(3) Develop and utilize new materials that exhibit reduced shrinkage and improved dimensional stability.
(4) Enable enclosure that maintain stable temperature to minimize environmental impact.

4. Threats

(1) Competitors may adopt new technologies or processes faster, potentially leading to market share loss.
(2) Dependence on specific filaments or materials that may not be widely available can hinder improvements.
(3) High-quality or specialized materials may come at a premium, increasing overall production costs.
(4) The need for specialized knowledge in operating and maintaining advanced FDM systems.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions

Azhar Equbal: formal investigation, methodology, manuscript writing; Ramesh Murmu: data curation; visualization; Veenit Kumar: resources, visualization; Md. Asif Equbal: supervision, validation.

Conflict of interest

The authors declare no conflict of interest.

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