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Review article

A study on fused deposition modeling (FDM) and laser-based additive manufacturing (LBAM) in the medical field

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A R T I C L E I N F O

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A B S T R A C T

Fused deposition modelling (FDM) and laser-based additive manufacturing (LBAM) are the essential technologies of 3D Printing under the technological platform of additive manufacturing (AM). This process involves layering tiny layers of a chosen material until the desired three-dimensional shape is achieved. FDM and LBAM have been commercialised and are also being deployed in a variety of medical fields. These technologies are worthwhile in reducing expenditures, increasing precision, and lowering operating and post-operative hazards, and the most crucial part is customisation. FDM is witnessing significant growth as an AM technology primarily because of its exceptional ability to construct functional parts with complex geometries. This study aims to investigate the effect of different process parameters such as build orientation, layer thickness, raster angle, air gap, printing speed, infill density, and extrusion temperature on the mechanical properties of FDM printed parts. This paper explores FDM and LBAM, the technological developments that have various applications in the medical field. Using a laser beam to fuse or melt successive layers of wire or powder material together to form three-dimensional objects is known as LBAM. It is one adaptable manufacturing process that is widely used to create metallic components with improved characteristics. By implementing FDM or LBAM technologies, surgeons can provide patients with precise and better information. The patient's adaption period for customised prostheses/implants is shorter, less painful, and less stressful. Where regular implants are often insufficient for some patients with complex circumstances, the ability to quickly manufacture personalised implants by using these technologies is quite helpful. This paper provides readers with an insight into the capabilities of FDM and LBAM in the medical field.

1. Introduction

Additive manufacturing (AM) is a technique used to fabricate parts layer-by-layer with the input of a Computer-aided design (CAD) file. With its ability to manufacture intricate geometries and customised components, AM has emerged as a disruptive force across various industries, ranging from aerospace and automotive to healthcare and consumer products. The process differs from traditional manufacturing methods that involve cutting or shaping material, while additive manufacturing uses only the required amount of material, minimising waste and conserving resources.

Additionally, rapid prototyping made possible by additive manufacturing enables designers and engineers to iterate and improve their designs swiftly. By drastically reducing time-to-market, this accelerated product development cycle gives businesses a competitive edge in today's quickly changing market environment. Implementing just-in-time manufacturing strategies is made more accessible by the capacity to swiftly generate functioning prototypes and parts on demand, which lowers inventory costs and streamlines supply chains.

Commercially, various types of additive manufacturing systems are available in the market, such as 3D printing, selective laser sintering (SLS), inkjet modelling, stereolithography (SLA), fused deposition modelling (FDM), and direct metal deposition (DMD). These systems vary in terms of how layers are built and the different types of materials

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that can be safely fabricated using these processes[1]

FDM is a popular AM technique that has gained significant prominence recently. FDM also referred to as Fused Filament Fabrication (FFF), is a type of 3D printing process that employs thermoplastic materials to produce three-dimensional objects. The fundamental principle behind FDM involves the controlled extrusion of a thermoplastic filament through a heated nozzle. The build material, thermoplastic filament, is fed into an extruder head during printing and heated to a predetermined temperature. The printing process is then started by extruding the molten filament through an extruder nozzle and depositing it line-by-line on a printing bed. The molten filament quickly cools down, solidifies, and sticks to the printer. The printing procedure is continued for the following layer, which is repeated until the entire object's design has been printed.[2] Fig. 1 shows the FDM setup.

Several FDM process variables significantly affect the manufactured parts. All these factors impact the bonding inside and between the deposited layers. A part with the desired attributes can be created by choosing the best possible arrangement of process variables. Utilising the optimum thermoplastic polymer for the component's intended application is also crucial.[3] As technological inventions grow, 3D printing can become a game changer for the industry and enterprises. 3D printing technology offers the ability to produce lightweight components with enhanced and complicated geometry in the aerospace industry, which can lower energy and resource requirements.[4]

One of the notable advantages of using FDM technology is the variety of filament materials that can be used to fabricate 3D-printed parts. The commonly used filament materials are Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA), Polycarbonates (PCs), Polyether ether ketone (PEEK), Polyetherimide (PEI), and Nylon. The additional materials, such as polyethene terephthalate glycol-modified (PETG), bio-composite filaments, high-impact polystyrene (HIPS), ceramic filaments, thermoplastic polyurethane (TPU), polyphenyl sulfone (PPSF) are not frequently used or studied as filament materials. Most of these materials are currently being developed or challenging to get on the market.[3] Therefore, this study briefly reviews the work done to enhance the strength qualities of FDM printed parts.

Using a laser beam to fuse or melt successive layers of wire or powder material together to form three-dimensional objects is known as laser-based additive manufacturing (LBAM). A wide range of materials, including thermoplastics, resins, and high-strength metal alloys, may be employed, and the technique can be applied to manufacture intricate forms precisely. Comparing the technology to traditional production processes reveals various advantages. Its main advantage is its capacity to build intricate structures with optimal geometry that would be challenging or impossible to construct using traditional methods. Compared to conventional production processes, the process's high precision and accuracy minimises material waste and energy usage while reducing the post-processing requirement.[5–7]

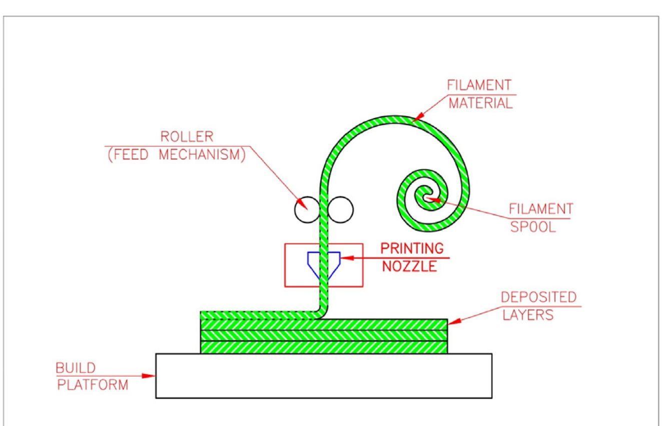

Fig. 1. Principle of FDM process.

It is highly configurable and automatable, efficiently used for quick prototyping and the economical production of small to medium-sized quantities of bespoke parts. The technique has also improved in recent years to the point that it can now be utilised for large-scale manufacturing, which is beginning in the industry. With the use of technology, items may be produced on demand, requiring no assembly and just the materials that are needed. It may be applied to drastically reduce the supply chain, allowing for the prompt and local production of parts. This lowers the production's time and expense requirements and the adverse environmental effects of waste and transportation.[8,9]

The study considers the different process parameters and optimisation of these parameters. Further, investigate their effect on the strength of the printed parts. Moreover, research gaps, challenges and industrial implications of the study are also suggested. This paper also studied the significant capabilities of FDM and LBAM in the medical field.

1.1. *Research objectives:*

The primary research objectives of this article are as follows:

Research objective 1:- The study investigates the influence of different process parameters on the mechanical strength of the FDM fabricated parts.
Research objective 2:- To assess the current state of research and identify gaps or areas requiring further investigation, aiming to provide insights for future studies and the advancement of FDM 3D printing technology.
Research objective 3:- To study the LBAM as a 3D printing tool and explore the effectiveness of its process parameters.
Research objective 4:- To identify the capabilities of FDM and LBAM for the medical field

By achieving these research goals, the paper aims to contribute to a thorough understanding of the connection between process variables and mechanical properties in FDM and LBAM, ultimately facilitating the development of improved manufacturing procedures and materials for this quickly developing technology and further discussed the significant capabilities of these both technologies for the medical field.

2. Literature survey

Numerous scholars have conducted extensive research on the process parameter optimisation of the FDM process. Most researchers focused on improving the parts' mechanical characteristics, surface finish, and dimensional accuracy. Table 1 shows the summary of the optimised parameters of FDM.

3. Research gap

The research finding shows that FDM applies to thermoplastic materials only, and most of the research is carried out on ABS and PLA materials. Therefore, future research can be made to use new filament materials, for instance, flexible filaments (TPU, TPE), composite filaments (carbon fibre, metal-filled), and high-temperature filaments (PEEK, ULTEM), which are tailored to particular needs and applications. Most of the research is concentrated on a few mainly influenced parameters such as layer thickness, build orientation, and raster angle. Several other parameters, such as filament colour, wall thickness, and several contours, must be explored for better dimensional accuracy and strength of the printed parts. Research on simultaneously optimising the different process parameters is limited. Only a few articles published considered multi-objective parameter optimisation. Another potential path for future research is additional investigation into multi-objective process parameter optimisations.

Furthermore, most of the research is concentrated on the parts'

Table 1
Summary of the optimised parameters of FDM.

Reference	Author/s	Material used	Process parameters	Outcomes measured	Remark
10	Afrose et al.	PLA	Build orientation	• Tensile Fatigue Properties of PLA Material. •Fatigue life	The 45° build orientation components exhibit a longer fatigue life for the same proportion of applied static stresses than the parts in the X and Y construction orientations.
11	Eryildiz	PLA	Build orientation	•Tensile strength •Build time	Tensile strength reaches a maximum for 0° orientation. Also, for upright (vertical) build orientation, 36% less tensile strength was obtained compared to flat orientation.
12	Wang et al.	Polyacetal material (POM)	Build orientation	•Tensile strength	The results of tensile verified tests show that the tensile strength values are highest for 0° specimens and lowest for 90° specimens. The 45° direction type's strength values were 65–72% of the sample's 0° direction values.
13	Petruse et al.	ABS	Build orientation	•Mechanical strength	The most significant influencing parameters for 3D printed components are build orientation and wall thickness. Finally, it is advised that the main load direction be parallel with the main fibre direction during the tensile loading of parts.
14	Syrlybayev et al.	PLA, ABS	infill density, infill patterns, extrusion temperature, layer thickness, nozzle diameter, raster angle and build orientation	•Tensile strength •Compressive strength	Layer thickness is the most critical factor among the studied ones. Furthermore, tensile strength decreases with increased layer thickness for both ABS and PLA filaments.
15	Wu et al.	ABS, PEEK	Layer thickness, raster angle	•Tensile strength •Compressive strength •Bending strength	It was concluded that layer thickness had more influence over the tensile strength and little influence on bending and compressive strength. Furthermore, it was observed that PEEK's tensile strength, Compressive strength, and bending strength were higher than that of ABS.
16	Frunzaverde et al.	PLA	Layer thickness, filament colour	•Tensile strength •Dimensional accuracy	Tensile strength shows a decreasing trend with an increase in layer height.
17	Moradi et al.	Nylon	Layer thickness, infill percentage, number of contours	•Maximum failure load •Parts weight •Elongation at break •Build time	Layer thickness is the primary variable for all responses. An increase in layer thickness resulted in a jump of 125–251% elongation at break.
18	Ziemian et al.	ABS	Raster angle	•Ultimate strength •yield strength •Impact strength	The test revealed that ultimate as well yield strength are maximum for 0° raster orientation, followed by the +45°/-45°, 45°, and 90° orientations in descending order.
19	Huang et al.	ABS	Raster angle	•Ultimate strength •Elastic modulus •Shear modulus	It was concluded that the ultimate tensile stress gradually decreased with increasing raster angle.
20	Ramiah and Pandian	ABS	Raster angle, raster width, raster to raster gap, build orientation, and layer thickness	•Tensile strength •Flexural strength •Impact strength	A significant impact of raster angle was observed on the strength of the parts.
21	Muhamedagic et al.	carbon fibre reinforced polyamide	raster angle, layer thickness, wall thickness and printing speed	•Tensile strength	Raster angle and layer thickness influence the tensile strength to a great extent. A tensile strength of 58.9 MPa was observed at 0° raster angle and 91.53 MPa at 90° raster angle.
22	Sood et al.	ABS	Layer thickness, raster angle, build orientation, air gap, and raster width.	•Tensile strength •Flexural strength •Impact strength	It was found that an increase in air gap resulted in better strength. Further, a small air gap restricts heat dissipation, resulting in stress accumulation.
23	Mishra et al.		air gap, layer thickness, raster angle, part orientation and contour width	•Compressive strength	It was found that the air gap between the raster significantly influences compressive strength.
24	Gebisa et al.	ULTEM 9085	air gap, raster angle, raster width, contour number, and contour width.	•Tensile strength	It was concluded that a low value of air gap resulted in better strength. Among the studied parameters, the influence of raster angle was the highest.
25	Algarni et al.	PLA, ABS, PEEK, PETG	Layer thickness, raster angle, print speed, infill percentage	•Mechanical strength	A comparative study was conducted on four materials depicting the study of printing speed. It was concluded that strength decreases for all materials with increased printing speed.
26	Miazio	Plastic	Print speed	•Tensile strength	The effect of printing speed on the FDM printed parts was investigated when varied from 20 mm/s to 100 mm/s. It was concluded that the strength of the sample decreases with an increase in speed.
27	Yang and Yeh	Wood, PLA	Print speed	•Compressive strength	The density of parts decreased with printing speed. Further, compressive stress decreases due to weak bonds between adjacent layers.
28	Rodríguez-Panes et.al	ABS, PLA	Infill density, layer thickness, layer orientation	•Tensile strength •Tensile yield stress •Nominal strain at break •Modulus of elasticity	The comparison was made between PLA and ABS. The result showed that the infill percentage significantly affected the mechanical properties. Furthermore, increasing the infill percentage improves the mechanical strength more for PLA than ABS fabricated parts.
29	Jatti el. al	PLA	Infill percentage, layer thickness, print speed, extrusion temperature	•Tensile strength •Flexural strength	It was concluded that extrusion temperature had a maximum effect on the impact strength.

(*continued on next page*)

Table 1 (*continued*)

Reference	Author/s	Material used	Process parameters	Outcomes measured	Remark
[30]	Hameed et al.	Acrylonitrile Styrene Acrylate (ASA)	Printing temperature, infill density, layer height, raster angle and printing orientation	•Impact strength •Tensile strength •Flexural strength	The highest impact and flexural strengths are achieved when the layer height and infill density are 0.08 mm and 100 per cent, respectively.
[31]	Tanveer et al.	PLA	Infill density	•Impact strength •Tensile strength •Impact strength	Infill density had a significant impact on the strength of the parts.
[32]	Rao et al.	Carbon fibre PLA	layer thickness, extrusion temperature, infill pattern	•Tensile strength	The interactions between layer thickness and infill pattern and infill pattern and extrusion temperature considerably impact tensile strength, according to an analysis of the tensile test data using ANOVA. The layer thickness of 0.1 mm, extrusion temperature of 225°C, and cubic infill pattern yield the greatest tensile strength of 26.59 MPa.

mechanical properties, dimensional accuracy, and surface finish. There are a variety of additional part characteristics, such as thermal properties, support materials, environmental properties, part shape complexity and other mechanical properties that are equally crucial for functional parts. These part properties must be optimised for the FDM components to be of higher quality. Future research in this area may take this as a position. Further in this paper, we have discussed additive manufacturing technology, known as LBAM, and the significant capabilities of both technologies for the medical field.

4. Process parameters associated with FDM as a 3D printing tool

The FDM process consists of several parameters, but build orientation, layer thickness, air gap, raster angle, infill density, extrusion temperature, and printing speed are the most studied parameters. Researchers have investigated several other process parameters over recent years. Alam et al. investigated the influence of nozzle diameter, nozzle temperature and feed rate on the surface finish of FDM printed specimens.[33]

The following is a description of the key process parameters.

- Build orientation - Build orientation describes how the components are positioned inside the build platform concerning the X, Y, and Z axes.
- Layer thickness is measured along the Z-direction (or the vertical direction of the FDM machine). It refers to the height (or thickness) of layers deposited after extrusion from the nozzle tip. It generally is less than the extruder nozzle tip diameter.[3]
- The raster angle is the direction (angle) about the build platform's X-axis where the extruded material is deposited. Raster angles typically range from 0° to 90°[3]
- Air gap - The gap between two adjacent rasters of the same layer is called the air gap.[29] It can be either positive, negative or zero.
- Printing speed - It is the speed at which the material-depositing nozzle tip travels across the build platform in the XY plane.[3]
- Infill density - Three-dimensional (3D) printer objects have solid exterior layers. The internal structure, often referred to as the infill, is an interior portion that is invisible and is covered by one or more exterior layers. It has a variety of shapes, sizes, and patterns. The percentage of infill volume filled by filament material is known as infill density.[3]
- Extrusion temperature - The temperature within the FDM heating nozzle before the material is extruded is called the "extrusion temperature."

5. Process parameter optimisation

Plenty of parameters in fused deposition modelling affect the printed part's overall quality. However, in this study, few standard parameters are considered, such as layer orientation, build orientation, raster angle, etc., which significantly affect the mechanical properties (tensile, compressive, fatigue strength). Most researchers optimised the process parameters to improve the dimensional accuracy., mechanical properties and surface finish of FDM fabricated parts. Different researchers use various techniques and tools to optimise these parameters. The following section describes research on different process parameters for optimising them.

5.1. Build Orientation

It describes the orientation of the component concerning the X, Y, or Z axis of the FDM machine inside the build platform and the angle at which it will be manufactured.[3] The build orientation impacts the overall cost of printing the pieces and their surface quality since they are constructed layer by layer.[30] Afrose et al. investigated the static and fatigue properties of PLA-fabricated parts using FDM technology. The result showed that the parts printed at 0° orientation exhibited a higher tensile strength of 60–64% as compared to 45° and 90°, respectively. On the other hand, when subjected to tensile cyclic loading, the parts with a 45° build orientation exhibit longer fatigue life than those of 0° and 45° orientation for the equal amount of applied static loads[10]

Eryildiz investigated the effect of different build orientations on the tensile strength and build time of FDM 3D-printed PLA parts. It was observed that tensile strength reaches a maximum for 0° orientation. Also, for upright(vertical) build orientation, 36% less tensile strength was obtained compared to flat orientation. Further, build time was also increased as the build orientation changed from flat to upright, and the number of layers for build orientation also increased, resulting in higher energy usage.[11] Y Wang et al. tested Polyacetal material (POM) as per ASTM D638 along three different directions, 0°, 45°, and 90° of the fused deposition modelling machine. The test piece made at a 0° angle has more mechanical strength than those made at 45° and 90°.[12]

Petruse et al. Pointed out in their experiment performed on 100 samples of ABS material that build orientation has the most influence over the mechanical properties of the tested specimen. ASTM D638- 02a type I samples are the most suitable for carrying tensile load on highly anisotropic plastic material. Moreover, during tensile loading of FDB fabricated parts, the main load direction was recommended to be parallel with the part's main fibre direction.[13]

5.2. Layer thickness

This is the height of the layers deposited along the Z-axis, which is typically the vertical axis of the FDM machine. It varies based on the nozzle's diameter and is often smaller than the extruder nozzle's diameter.[3] Syrlybayev et al. studied seven process parameters, finding that layer thickness is the most important among all the parameters.[14]

Wu et al. used five samples to investigate the effects of raster angle and layer thickness on the mechanical characteristics of polyether-ether-ketone (PEEK). PEEK was 3D printed to create samples with three-layer thicknesses (200, 300, and 400 μm) and three raster angles (0°, 30°, and 45°). Tensile, compressive, and bending strengths were then measured. An authorised universal materials testing apparatus fitted with a 50-kN load cell was used for mechanical testing. According to all mechanical tests, the samples built with a 300 m layer thickness and a raster angle of 0°/90° exhibited the most significant strengths.

Additionally, samples with a 400 μm layer thickness showed a considerable loss in strength. It was also concluded that layer thickness had more influence over the tensile strength and little influence on bending and compressive strength.[35] Furthermore, a comparison was made between the mechanical properties of ABS-printed parts under similar conditions. PEEK's tensile, Compressive, and bending strength were higher than that of ABS.[36] Apart from strength criteria, the literature also shows that varying layer thickness also affects the dimensional accuracy of the parts.

Frunzaverde et al. researched the PLA Specimen by varying the filament colour (a less studied parameter) and the layer height for different samples. It was found that filament colour and layer thickness influenced the dimensional accuracy and the tensile strength of the part to a great extent. The variable parameters were the layer height (0.05 mm, 0.10 mm, 0.15 mm, 0.20 mm) and the material's colour (natural, red, grey, and black). The result revealed that the colour of PLA had a significant effect on the tensile strength. The tensile strength showed a decreasing strength with an increase in layer height. Furthermore, it was concluded that the effect on tensile strength is maximum for filament colour, followed by layer thickness.[16]

Moradi et al. used the statistical tool to study the influence of layer thickness, infill percentage and the number of contours on the mechanical properties, part weight and build time for Nylon printed parts by FDM. A reduction in layer thickness for the same printing speed resulted in greater strength and less elongation as the cooling rate increased with the decrease in layer height. Further, as layer thickness was raised from 0.15 mm to 0.55 mm, it resulted in a 125–251% increase in elongation at break.[17]

5.3. Raster angle

Raster angle is one of the most crucial process variables affecting mechanical behaviour, affecting the anisotropy and, consequently, the strength of the FDM parts.[37] Ziemian et al. conducted several experiments on ABS filament to test various mechanical properties by using four raster orientations (0°, 45°, 90° and +45°/-45°). The test revealed that yield, ultimate, and impact strength are maxima along 0° raster orientation. Due to their most extended effective raster lengths, 0° rasters provide the most significant resistance to bending. The compression test reveals that the 45° raster specimen is comparatively weaker than other raster orientations.[18] Similar findings were investigated by Huang et al. by conducting an experimental and analytical approach to FDM printed parts. It was concluded that the ultimate tensile stress gradually decreased with increasing raster angle according to the findings of tensile tests performed on samples constructed with different raster angles.[19]

Ramiah and Pandian investigated five parameters (raster angle, raster width, raster to raster gap, build orientation and layer thickness) influencing the strength using the multi-objective optimisation technique and studied the interaction between the parameters using ANOVA. The parameters were varied to study their effect on the Tensile, flexural and Impact strength of ABS printed parts. The study concluded that the outputs are more influenced by the raster angle (34.13%), raster width (32.54%), and layer thickness (31.72%). In contrast, the other factors, such as raster to raster gap (8.03%) and part build orientation(8.05%), have less of an impact.[20]

Muhamedagic et al. investigated the influence of four parameters, namely, raster angle, layer thickness, wall thickness and printing speed, to study the tensile strength of FDM printed carbon fibre reinforced polyamide material using RSM (response surface method) and ANN (artificial neural network). The findings demonstrate that the most critical factors affecting tensile strength are layer thickness and raster angle. A tensile strength of 58.9 MPa was observed at 0° raster angle and 91.53 MPa at 90° raster angle. Thus, it depicts a significant increase in tensile strength with increasing raster angle.[21]

5.4. Air gap

The gap between two adjacent rasters of the same layer is called the air gap.[34] It can be either positive, negative or zero. The deposited materials are in contact when the air gap is zero. The positive air gap results in a loosely packed structure, whereas a negative air gap results in a denser structure.[38] Sood et al. investigated the effects of air gaps on the FDM-processed parts. It was concluded that zero air gap resulted in better diffusion between adjacent rasters but, on the other hand, decreased heat dissipation. Further, a positive air gap increases strength (tensile, flexural) at lower layer thicknesses by increasing heat dissipation. Therefore, strength increases with air gap.[22]

Mishra et al. adopted the DOE technique to investigate the influence of six process parameters, such as air gap, layer thickness, raster angle, part orientation, raster width, and contour number, on the compressive strength of the FDM printed specimen. It has been found that the compressive strength of FDM-built components is significantly influenced by part orientation, contour number, and air gaps between rasters.[23] Gebisa and Lemu. The influence on tensile strength for the ULTEM 9085 fabricated part was reported by studying five process variables: air gap, raster angle, width, contour number, and contour width. Complete factorial design of the experiment was performed with low and high-level air gap values of −0.0254 mm and 0.00 mm, respectively. It was found that low-level air gap values have higher tensile strength (86.92 MPa) as compared to high-level air gaps. Also, the effect of the air gap is more noticeable at a 90º raster angle than at a 0º raster angle.[24]

5.5. Printing speed

During extrusion and deposition, the nozzle's horizontal speed on the build platform is called printing speed. Typically, it ranges from 15 to 90 mm/s.[25] M Algarni et al.[25] prepared a comparative study on printing speed for four different types of materials. PLA, ABS, PEEK, and PETG using the ANOVA technique. The effect of varying printing speed on different materials is described below:

- Polylactic acid (PLA): The study demonstrates that Young's modulus is not altered by more than 20% while printing at different speeds (70, 80, 90, 100, and 110 mm/s). Additionally, faster printing speeds impact the filament's melting characteristics and lead to poor layer-to-layer adhesion, which reduces strength.
- Acrylonitrile Butadiene Styrene (ABS): In a study published in extruder temperatures of 230°C and 270°C, varying layer thicknesses (0.1 and 0.3 mm) were used to examine the impact of printing speed on ABS tensile strength. The study revealed that tensile strength decreased with increased printing speed for all extruder temperatures and layer thicknesses.
- Polyether Ether Ketone (PEEK): The study looked at how four different printing speeds—17, 20, 23, and 26 mm/s and varying layer thicknesses affected the tensile strength of the material. The findings demonstrate that increased printing speed resulted in lower extrusion width, which weakens the peek-printed objects regardless of the thickness.
- Polyethylene Terephthalate Glycol (PETG): The study resembles the same result as provided by the above materials, i.e., tensile strength and flexural strength decrease with printing speed regardless of the layer thickness. Moreover, the hardness of the parts (BHN) increased with printing speed.

Lukasz Miazio investigated the effect of printing speed on the FDM printed parts when varied from 20 mm/s to 100 mm/s. It was concluded that the strength of the sample decreases with an increase in speed..[26] Teng Chun Yan et al. studied the effect of varying printing speeds 30–70 mm/s on the printed WPC (Wood/PLA) part. It was observed that the density of the parts decreased with an increase in printing speed. Moreover, the sample's compressive strength decreases with increased speed due to the weaker bonding between the adjacent layers.[27]

5.6. Infill percentage

Infill percentage is one of the significant parameters that impact the strength of the FDM printed parts. Rodríguez-Panes et al. compared the effect of infill pattern on the ABS, and PLA fabricated parts. It was observed that an increase in infill percentage from 20% to 50% significantly improved the mechanical strength by 27% for PLA and 25% for ABS-printed parts.[28] Jatti et al. studied the effect of different infill percentages on tensile strength, impact strength, and flexural strength for the PLA fabricated parts. Mathematical models were developed using nonlinear regression. The range of optimum infill percentage chosen was 70–100%. It was found that the tensile strength, flexural strength, and impact strength increase with the increase in infill percentage[29]

Hameed et al. studied the effect of varying process parameters on the thermoplastic ASA (Acrylonitrile et al.) polymer filament fabricated using FDM. The L18 orthogonal array experimental design was conducted to see the effect on various mechanical properties. It was found that infill density and layer height had the most impact when it came to the fabrication of 3D-printed parts. Furthermore, the highest impact and flexural strengths are achieved when the layer height and infill density are 0.08 mm and 100 per cent, respectively.[30] Tanveer et al. investigated the influence of variable infill density on the PLA specimen fabricated using FDM technology. The tensile and impact tests were performed at 50%, 70%, and 100% infill density, respectively. It was concluded that impact strength is directly proportional to infill density.[31]

5.7. Extrusion temperature

Extrusion temperature refers to the temperature maintained inside the heating nozzle of the FDM before the material is extruded.[3]

Extrusion temperature is one of the critical parameters affecting the strength of FDM fabricated parts. Since the FDM process is more prone to thermal degradation due to the high temperature involved, an excessive temperature will result in void generation, thereby impacting the final strength of the product. Moreover, low temperature, then recommended, will not melt the material, resulting in clogging of the nozzle. Therefore, an optimum temperature is required for a better-quality product.[39]

Jatti et al. employ response surface methodology (RSM) to optimise various process parameters, including the extrusion temperature. The experimental runs were conducted within the limits of semi-liquid materials, with the extruder temperature set at 190, 200, 210, 220, and 230 °C. Tensile, flexural, and impact test specimens were prepared per ASTM standards and tested on UTM of VEEKAY TESTLAB and an impact testing machine of ADVANCE EQUIPMENTS. It was concluded that extrusion temperature had the maximum effect on impact strength.[29]

Rao et al. Studied the effect of three parameters, layer thickness, extrusion temperature, and infill pattern, on the tensile strength of carbon fibre PLA fabricated parts via FDM. Further, ANOVA analysis was conducted to determine the interaction between different parameters. It was concluded that infill pattern-extrusion temperature significantly affects the tensile strength. Furthermore, the sample with the highest tensile strength value, 23.56 MPa, had an extrusion temperature of 225 C, whereas the sample with the lowest value, 21.47 MPa, had an extrusion temperature of 205 C. Therefore, the tensile strength increases as the temperature rises.[32]

6. Significant challenges in FDM technology

This section outlines the fundamental discoveries, weaknesses, and future directions for studying the FDM process parameters. One of the issues with the FDM technology is the strength of the parts produced in comparison to the conventional manufacturing process, the reason being that in most of the reviewed literature, it was found that the majority of the work is done in optimising the tensile strength of the parts the compressive and flexural strength are the least analysed properties. Thus, more research needs to be done on the fabricated part's dynamic properties to enhance its strength. This can be done using hybrid filament materials, including bioplastic, bio composite or a combination of thermoplastic blends. Another challenge with the FDM is that only a few papers have employed multi-objective optimisation methods to produce a collection of optimal solutions, which has narrowed down the scope to interpret the optimisation of these parameters accurately. Hence, future research can study the multi-objective optimisation of these parameters to understand the conflicting parameters better.

7. Some process parameters of LBAM

The main process parameters involved in LBAM are scanning speed, Hatch distance, Layer thickness, Laser power, and powder feed rate. Different researchers are conducting extensive research to optimise these parameters.[40,41]

As witnessed in the past decades, extensive research has been carried out in metal LBAM processes. The control of process parameters in LBAM processes is difficult due to the variation in porosity formation and thermal history. Defects generated in the physical AM parts are due to the incomplete fusion of metal powder particles in AM processes, which depends on the selection of laser process parameter settings. The process parameters also significantly affect the microstructure, texture, porosity and surface quality due to the fusion of powder, dilution and variation in solidification time. Optimisation of laser process parameters based on minimum dilution and porosity is a significant solution to fabricating defect-free metal AM parts. However, apart from optimum laser process parameters, the build parameters, including scan strategy and build orientation, also play an essential role in the variation of residual stresses and anisotropy of AM parts.

LBAM processes are also gaining interest in the medical industry due to their ability to generate custom-specific metallic implants from various biocompatible materials. For the robustness, repeatability and consistent performance of LBAM parts for medical applications, the LAM process parameters must be investigated deeply for large-scale adoption of LBAM. The major work on some process parameters on LBAM are as follows:

Kempen *et al.*[42] reported that the effect of an increase in scan speed (120–600 mm/s) and layer thickness (30–60 μm) with constant laser power of 100W leads to a decrease in density and micro-hardness. They also re-melted the deposited layer before adding a new layer to increase the density. A maximum density of 99.4% is achieved, but production times increase.

Zhang *et al.*[43] investigated the influence mechanism of process parameters on the relative density based on an orthogonal experiment. They found the maximum relative density of 99.19 % using Archimedes' principle for 160 W (laser power), 400 mm/s (scan speed), and 0.07 mm (scanning space) parameter settings. The large scan spacing generates unmelted powder due to spatter formation, leading to low-density parts. The formation of overlapping zones depends on the scan spacing, as shown in Fig. 2.

Rashid *et al.*[44] studied the effect of single- and double-layer scan strategies on the density and metallurgical properties of SLMed 17-4 PH stainless steel in as-fabricated and heat-treated conditions. They found higher relative density for the double scanning strategy owing to remelting, and the high hardness obtained is attributed to a higher martensite phase fraction than the retained austenite. The heat treatment generated a uniform distribution of tempered martensite with a small fraction of austenite, enhancing hardness. A single scan strategy developed gap valleys between the tracks, forming pores due to unstable melt flow in the opposite direction. Double scan remelting of the solidified layer improved the inclusion of pores and the balling effect phenomenon.

Geiger *et al.*[45] tailored the texture of SLMed Inconel 738LC by adopting specific scanning strategies during stacking and correlated the generated anisotropy with forming textures. They reported the possibility of switching the transverse anisotropy into transverse isotropy in triply layered stacked samples. The alignment of grains was decided by the orientation of the thermal gradient, leading to the formation of crack-free parts.

Kudzal *et al.*[46] investigated the effect of scan patterns in powder bed fusion AMed 17-4 PH stainless steel. They adopted six different scan patterns, including hexagonal, concentric, longitudinal uni-directional, bi-directional, lateral uni-directional, and bi-directional. X-ray diffraction (XRD) analysis determined the phase fraction variation due to a change in scan length for various scan strategies leading to a variation in mechanical properties. The short laser scan length decreased the thermal gradients within the layers, resulting in reduced thermal stress and heat distortion.

Ahmadi *et al.*[47] analysed the effect of various laser scan strategies (unidirectional, bidirectional and cross-hatching), as shown in Fig. 3, on the mechanical properties of SLM 316L. They found increased mechanical properties for the cross-hatching strategy due to the reduced porosity, un-melted zones and long columnar dendrites. However, columnar dendrites were found along the scan directions for uni-directional and bidirectional scan strategies.

Gu *et al.*[48] reported the role of hatch style and part placement strategy on SLMed 316L stainless steel. They found that crystallographic variations significantly affect mechanical properties by modifying the orientation relationship between texture and grain growth. This effect is due to double stagger melt with 90º rotation having a <001> strong texture in the transverse direction, resulting in high toughness, ductility and strength.

Sun *et al.*[49] optimised the process parameters for Ti–6Al–4V cladding on Ti–6Al–4V substrate using Nd: YAG laser. They observed that the powder feed rate significantly affects the track width and height, and the scan speed is dominant in the track depth. They also reported that an increase in scan speed leads to a decrease in dilution of the track. However, the scan speed harms the track width-to-height (w/h) ratio. With an increase in laser power, there is an increase in track depth and w/h ratio.

8. Capabilities of FDM and LBAM towards the medical field

In contrast to conventional methods, FDM and LBAM are manufacturing technologies that use an additive process to create three-dimensional items. By using materials like polymers, wire, powder, metals, and ceramics, this technology creates items layer by layer as an alternative to sculpting raw materials through subtractive operations like grinding, cutting, or machining. These items are created using digital files, which may be altered. Before performing surgery, the optimal places for stabilising screws or plates that adhere to the patient's bone model surface are planned and tested using both surgical guides and anatomical models, often known as bone models, which are frequently made using this technology.[50–55] The significant capabilities of FDM and LBAM for the medical field are discussed in Table 2.

Specific clinics have created protocols that allow surgeons to plan and practise treatments using inexpensive mannequins implanted with patient-specific AM models to cut costs.[56–58] Surgeons can now better understand precisely how a procedure needs to be performed, down to the touch and feel of the various parts of a patient's anatomy. By using this technology, doctors may produce guides that precisely locate drills or other surgical tools by following each patient's unique anatomy. Improved postoperative outcomes are achieved by precisely placing restorative therapies, including screws, plates, and implants, with the use of AM guides and tools.[59–63]

9. Comparing FDM and LBAM in the medical field

LBAM had a faster production rate of medicines than FDM as the former does not require time to dry up, whereas FDM requires 48 h to evaporate the solvent. Moreover, not all medicines can be produced by SLS as the high laser temperature can degrade the drug's quality.[64] Ali et al.[65] and Abilgaziyev et al.[66] studied the different printing technologies based on a multi-material 3D printing setup. The FDM platform was more straightforward and cheaper than the available printers on the market.

10. Significant contributions to the work

Comprehensive literature review: One of the main contributions of this study is its thorough and organised analysis of the literature on the impact of process parameters on the mechanical characteristics of FDM printed parts. The paper study examines and synthesises findings from multiple studies to provide a comprehensive overview of the present state of knowledge in this field. Researchers, engineers, and professionals can use this as a valuable resource to learn more about the connection between the parameters of the FDM 3D printing process and mechanical qualities.

Identification of critical parameters: Another significant contribution is the identification of key process parameters that have a substantial influence on mechanical properties. The study emphasises the significance of factors affecting part strength and durability, such as layer height, build orientation, and printing temperature. This knowledge can help practitioners and researchers prioritise their work when improving FDM printing processes.

Material-Parameter Synergy: The paper recognises the intricate interplay between material selection and process parameter optimisation. It emphasises the importance of considering both aspects to achieve superior mechanical properties. This holistic approach acknowledges that choosing filament material and manipulating process parameters is crucial for obtaining the desired mechanical performance in FDM printed parts. This perspective can guide material engineers and designers in creating materials tailored to specific printing conditions.

Optimisation strategies: The paper discusses various techniques to improve the mechanical properties of the FDM printed parts. With this

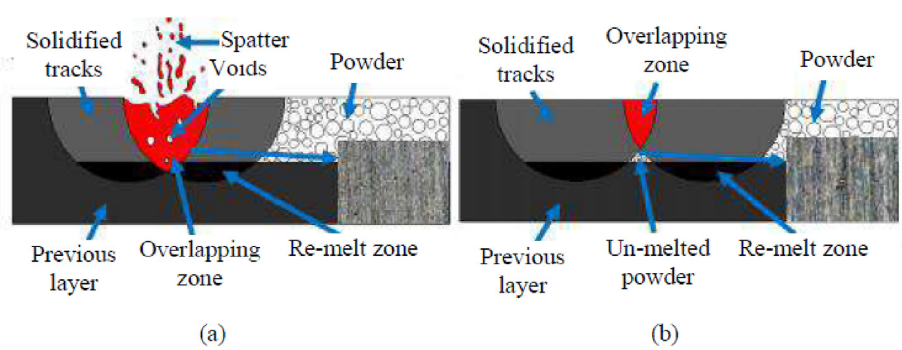

Fig. 2. Scan space effect on the overlapping zone (a) large spacing and (b) small spacing.[43].

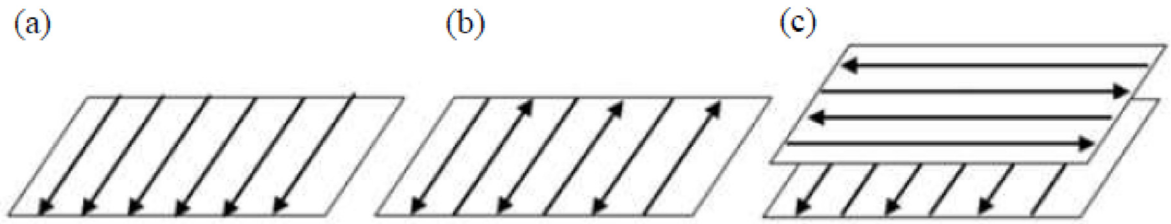

Fig. 3. Schematic of scan strategies: (a) unidirectional, (b) bidirectional and (c) cross-directional[47].

information, readers are better equipped to fine-tune printing parameters to meet multiple mechanical performance objectives, such as maximising strength, enhancing impact resistance, or striking a balance between various qualities.

Real-life applications: It delivers concrete advantages to researchers and Industry professionals by revealing how process variables affect mechanical qualities. Engineers and manufacturers can use this information to create high-quality, mechanically durable printed components for various industries, from aerospace and automotive to healthcare and consumer goods.

Medical applications: These technologies help create 3D prosthetics and other medical implants for better surgical planning, teaching and learning processes. This improves the efficiency of the healthcare. Medical implants, including knee and hip implants, can be personalised via FDM LBAM. Complex, patient-specific designs may be created by using this technology, which can help patients heal more quickly and have better results. Moreover, prosthetic limbs, surgical instruments, and medication administration systems may be made using it. With this technology, healthcare may reduce costs and lead times while improving product performance, efficiency, and dependability by creating highly customised, accurate, and complicated parts.

Custom prostheses may be made via 3D printing to fit each person's unique anatomy precisely. The goal of personalised prostheses is to improve functionality and comfort. Before performing complicated operations on a patient, surgeons may practise them on 3D-printed replicas. This enhances surgical results and lowers the possibility of mistakes. Specialised surgical instruments are entering a new age by using this technology. Surgeons can use devices explicitly designed for a treatment or patient's anatomy. This degree of personalisation speeds up patient recuperation and lowers the chance of mistakes. Accurate incisions and implant placement are facilitated using 3D-printed surgical guides and templates. Both patients and medical personnel gain significantly from this technology, which expedites surgical procedures. AM's cost-effective, iterative prototyping methods make tool design optimisation possible. Anatomical reproductions produced by these technologies have revolutionised pre-operative planning and medical education.

11. Future scope

As we look towards the further development of FDM technology, various potential directions for additional study and investigation can be considered.

Advanced Material Investigations: Upcoming studies may examine how process variables affect the mechanical characteristics of FDM-printed objects made of unique, high-tech materials. Investigating the effects of factors on materials such as composite filaments, biodegradable plastics, or high-performance thermoplastics may be of great interest.

Recycling and sustainability: Research might concentrate on maximising FDM parameters for sustainable practices, such as recycling and material reuse. Investigate how process variables can be changed to improve printed parts' mechanical qualities from recycled materials or other eco-friendly resources.

Artificial intelligence & machine learning approach: Investigate incorporating artificial intelligence and machine learning approaches to forecast the ideal process parameters based on desired mechanical attributes and material characteristics. This can result in an automated parameter selection process that is more effective.

Multi-material printing: Examine how different process variables, such as dual extrusion or multi-material FDM, simultaneously affect printing with many materials. It will be essential to comprehend how these characteristics affect the bonding and interaction between multiple materials for various applications.

Environmental Impact: In this changing world order, climate change and global warming have become a key influencer in almost every sector. Thus, manufacturing companies are adopting strict guidelines under government regulations to ensure the environment's safety. Therefore, it is essential to thoroughly analyse the environmental effects of the FDM 3D printing processes, considering various process variables and materials. This can aid in comprehending how FDM technology may affect sustainability.

Real-world applications: Apply the study's findings to practical applications in industries like architecture, automotive, aerospace, and medicine by using optimised process parameters. Analyse the effectiveness and robustness of FDM printed components in various sectors.

Standardisation and Quality Control: Sharing knowledge about the effects of process parameters on component quality may help the industry build standards for FDM printing. Examine quality control procedures and systems to guarantee dependable and consistent mechanical performance.

Future Medical Applications:- In future, a vast array of biocompatible materials will be used for AM technologies, and further techniques for working with metals, polymers, or ceramics are being developed. Furthermore, because of the technology's extraordinary degree of design flexibility and capacity to make lot sizes of one at a reasonable cost, goods may be precisely customised to satisfy a patient's needs, including precise geometric fit and particular load-bearing behaviour. A customised product design is produced using digital reverse engineering and recorded patient data. Examples of such customised items are prosthetics, surgical equipment, and artificial joint or bone replacements. Together, they improve the patient's condition and the course of therapy.

12. Conclusion

The paper extensively explored the influence of printing parameters on the mechanical properties of FDM fabricated parts. This article reviews the research work done to determine and optimise the different process parameters in FDM. Reviewing the existing literature concluded that various process parameters such as layer thickness, build orientation, raster angle, air gap, printing speed, infill density, and extrusion temperature significantly impacted the parts' strength. Medical professionals can use 3D replicas made from patient imaging data as concrete models for practice and surgery planning. These 3D-printed models allow surgeons to practise complex surgeries and improve their methods, which boosts their confidence and skill set. Surgery becomes more accurate and effective, lowering risks and surgical complications. With this technology, it is now feasible to produce items precisely tailored for each patient, such as casts or, even more advanced, prostheses and implants.

The key findings of the research are described below:

Table 2
Significant capabilities of FDM and LBAM for the medical field.

S. No	Capabilities	Description
1.	Implement changes in medical implants.	Even minor changes in implant design take a long time to implement using traditional production methods. The designer may now easily tweak and construct a new implant using 3D printing technology. This procedure is faster and less expensive than previous implant design procedures. The designer can double-check the prototype for accuracy and make any necessary modifications to the final product quickly. Titanium has been allowed for use in these 3D printers and can aid in the production of implants.
2.	Guidance of operation in an effective way	Surgeons can use 3D-printed models to help plan their surgeries and even use them for guidance during operations. Some doctors would even perform the surgery on the 3D-printed replica beforehand to better prepare them for the real thing. Testing and planning are two significant advantages of 3D printing in the medical. It is critical to be able to test therapies or implants on precise replicas. 3D printing can speed up the creation of novel products by enhancing collaboration between engineers and medical specialists.
3.	Customised replacement joints	Implants and devices made with 3D printing have much potential. It can produce a specialised device or a customised replacement joint on the spot for a surgeon who needs it. Orthopaedics is one of the more promising medical fields for 3D printing compared to soft tissue and organs. 3D-printed structural replacement implants for the knees or hips that are tailored for each patient would be a huge medical breakthrough. This would be groundbreaking, given the hundreds of knee replacement procedures performed each year. The common materials for knee replacement, cobalt chrome and titanium, have design limits that 3D printing using polymer materials must overcome.
4.	Innovative Surgical guides	Innovative Surgical guides can also be made via 3D printing. These guides can be used to make precise bone slices during surgery. This procedure cuts down on surgery time and has far-reaching ramifications for the patient, surgeon, and hospital. The length of the procedure, as well as its efficiency, can be reduced while still providing superior patient results. Using precise 3D printed guidance templates that fit directly onto the bone, cases like complicated abnormalities can be dealt with more efficiently.
5.	Customised therapy	The ability of a surgeon to comprehend the complexities of a patient's musculoskeletal system is primarily determined by the ability to read medical imaging. These technologies can help patients get more customised therapies by removing the need for radiological knowledge. With a physical model, these helps improve comprehension of a patient's specific anatomy. This physical model can improve preoperative surgical planning, resulting in more precise implant placement and better surgical results. These technologies can also create bespoke implants tailored to a patient's anatomy.
6.	Minimise the rate of reoperation.	3D printed models minimise the reoperation rate and aid in surgical planning and novice surgeon training. Using a 3D-printed model to examine the surgical approach for corrective osteotomies has become increasingly popular over the last several years to acquire a more comprehensive anatomy picture and improve planning details. Compared to typical 2D radiological imaging, surgeons can now evaluate patient anatomy more concretely with online 3D Printing services, allowing for improved, more detailed surgical planning.
7.	Print innovative anatomical structures.	These can now print considerably larger innovative anatomical structures in one piece, such as the entire spine and rib structures. As a result, a 3D model is becoming a more valuable tool for clinicians treating complex patients. Scaffolds and implants that mimic the biomechanical qualities of bones are required in regenerative medicine. Porous implants can repair or replace damaged bones since they are developed with tailored mechanical performance using state-of-the-art topology optimisation and manufactured using additive manufacturing.
8.	Customised Scaffolds	Porous scaffolds often comprise many irregularly shaped pores of various sizes. As a result, quantitative analysis of their properties is relatively easy. Researchers frequently presume that scaffolds are made up of periodically repeating unit cells in all directions and that the design of the micro-unit cells may clearly describe the scaffolds' macro features. The scaffolds are implanted in a complicated environment, and various circumstances influence their performance. Some of them, such as high permeability and stiffness, compete with one another since a greater pore size is usually acquired at the expense of lesser mechanical strength. As a result, it increases mass transfer while maintaining a robust supporting structure.
9.	Cost-effective and innovative approach	When it comes to bespoke orthopaedics and prosthetics, 3D printing has proven to be a more cost-effective and innovative approach when compared to other technologies. Furthermore, due to the parameters that these prostheses can supply, the quality of these prosthetics is quite good. This technology saves time and money while still receiving a high-quality product. Many 3D printers can now print considerably larger anatomical structures, such as the entire spine and rib structures, in one piece. 3D printing is an increasingly essential capability for spine surgeons treating challenging patients worldwide. The orthopaedic design and technology business may have foreseen this shift to making essential in-house medical equipment using additive materials.
10.	Explanation of surgery in an innovative way	Physicians can utilise patient-specific surgical models to explain the surgery innovatively ahead of time, which improves patient consent and reduces anxiety. New biocompatible medical 3D printing materials have also enabled the development of new surgical equipment and techniques to improve the clinical experience during surgery. These include sterilisable fixation trays, contouring templates, and implant sizing models that may be used for implants before the initial incision, allowing surgeons to save time and improve accuracy during complex surgeries.

- It was observed that most of the research is concentrated on tensile strength; other properties, such as shear strength, flexural strength and impact strength, also need to be investigated.
- Most of the research uses two materials, mainly ABS and PLA. Thus, other materials, such as smart, bioplastic, composite, and PEEK, can produce better part characteristics.
- Researchers study parameters such as layer thickness, build orientation, and raster angle in contrast to other process parameters such as

shell width, filament colour, number of contours, and print speed. The least studied parameters may be considered for future research.

- As stated above in the literature, optimisation of multi-objective process parameters is one of the potential areas of research for further studies.
- In the medical field, FDM and LBAM can assist in reducing surgical risks and, in some situations, make the procedure more efficient. Anatomically realistic models of a patient's body can assist surgeons in choosing how to intervene with more precision, much as 3D-printed instruments can help speed the surgical process.

Furthermore, by reviewing the current literature, various statistical tools were used by different researchers to optimise these process variables. The results of this research emphasise how crucial it is to correctly choose and optimise these parameters to achieve desired mechanical properties in FDM printed parts. The paper highlights the impact on tensile, compressive, bending, yield, and ultimate strength by varying process parameters. Researchers, engineers, and manufacturers can benefit significantly from the knowledge gained from this review to optimise the printing procedure, improve part performance, and realise the full potential of FDM technology in various applications, from rapid prototyping to functional end-use parts.

AM technologies are frequently utilised to create prosthetic models tailored to each patient's anatomy, ensuring a precise fit. It is used in places where prostheses come into touch with patients because of its capacity to create intricate geometries from various materials. It has been utilised to develop a wide range of products, from comfortable prosthetic leg connections to intricate, highly personalised facial prosthetics for patients. Surgeons can minimise post-operative pain and operation time with the quick production of sophisticated implant models. The capacity to quickly create personalised implants solves a recurring issue in orthopaedics, where conventional implants frequently fall short. Previously, doctors had to manually modify implants of a specified size or undertake invasive bone transplant procedures.

Data availability

This is study-based paper. We have taken data from various research papers and cited in the text and reference list.

CRediT authorship contribution statement

Minhaz Ahmad: Writing – original draft, Methodology, Investigation, Conceptualization. **Mohd Javaid:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Abid Haleem:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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