Advanced Engineering Letters **Vol.5, No.1, 12-25 (2026)** **e-ISSN: 2812-9709**

Fused Deposition Modelling in Additive Manufacturing: A Comprehensive Review of Polymer-Based Processes, Properties, and Applications

UDC:678.7:621.78
Review
https://doi.org/10.46793/adeletters.2026.5.1.2

S. Gopalakrishnan[1], N. Senthilkumar[1*], B. Deepanraj[2], Muhammad Asad[2], G. Perumal[3]

[1]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, SIMATS, Chennai, 602105 Tamil Nadu, India
[2]Department of Mechanical Engineering, College of Engineering, Prince Mohammad Bin Fahd University, 31952 Al Khobar, Saudi Arabia
[3]Department of Mechanical Engineering, V.R.S. College of Engineering and Technology, Villupuram, 607107 Tamil Nadu, India

Abstract:
Fused deposition modeling (FDM) is the preferred approach in polymer additive manufacturing (AM) owing to its design flexibility, the availability and affordability of materials, and printing consistency and performance constrained by processing-degradation interactions. This review focuses on FDM, a technology that demonstrates outstanding efficiency due to its adaptability and facilitates productivity in the rapid prototyping of complicated geometries. The microstructure, impact toughness, tensile strength, and wear resistance of the produced components may be studied by examining the influence of variables, viz., infill density, printing speed, layer thickness, nozzle diameter, and extrusion temperature. Investigators take a comprehensive look at thermal deterioration and how post-processing changes its attributes. The performance-enhancing effects of strands modified with nanomaterials and the microstructural development of printed components are also highlighted. The benefits of using machine learning on FDM for fault estimation, closed-loop monitoring, and attribute-targeted inverse design are also discussed. The reusability of FDM-printed components and their impact on the green economy are evaluated. In addition, several applications of functionally dense matrix components with tight tolerances are discussed, along with possible avenues for future study in state-of-the-art methods such as smart polymers and 4D printing.

ARTICLE HISTORY
Received: 1 September 2025
Revised: 12 January 2026
Accepted: 29 January 2026
Published: 31 March 2026

KEYWORDS
3D Printing, Additive manufacturing, Fused deposition modelling, Build orientation, Raster angle, Productivity

1. INTRODUCTION

3D printing has been at the forefront of the manufacturing shift due to its ability to produce intricate designs while precisely controlling the resources at hand [1]. In AM (additive manufacturing), components are developed layer by layer, starting from a 3D model, as compared to the traditional mode of eliminating material [2]. Because of AM's innovative nature, complex designs may be created that were earlier unattainable/challenging to produce using various traditional approaches. Multiple methods are involved in AM, and individually has its own advantages, limitations, and potential uses. Powder Bed Fusion (PBF) is one of the procedures considered in metal AM [3]. Electron beam melting (EBM) [4], direct energy deposit (DED) [5], and selective laser melting (SLM) [6] are among the several processes that it integrates. The

---

[*]CONTACT: N. Senthilkumar, e-mail: nskmfg@gmail.com

establishment of complicated designs and parts has been transformed by these procedures, which have been immensely beneficial to the aviation, medical services, and other industrial sectors. The core technologies of the evolving field of polymer AM are Fused Deposition Modelling (FDM), which builds structures by extruding thermoplastic strands, Selective Laser Sintering (SLS), which creates designs by incorporating polymer powders into structures, and Stereolithography (SLA), which brings accuracy to existence via photopolymerization [7].

The use of these technologies in functional end-use components, personalised consumer products, and rapid prototyping (RP) has been extensive. In the 1980s, Charles Hull developed AM with the development of the first SLA device. This revolutionary method paved the way for AM built for polymers. The range of applications was expanded in the 1990s with the invention of other vital processes, such as FDM and SLS. Metal AM emerged much later, with significant advancements occurring in the early 2000s and the late 1990s [8]. With the introduction of EDM and SLM, it is now possible to mass-produce mechanically comparable, dense metal parts that were previously produced using a conventional manufacturing approach. AM is reforming the engineering division by low-cost part fabrication, minimizing production delays, and providing designers with design freedom [9]. A significant state in AM is the manufacture of intricate, light-weight metal assemblies for the transportation and aviation industries. Further, customized implants and prosthetic parts are produced with AM that triggers an immense change in the healthcare divisions [10]. The polymer product development cycle is intensely affected by AM's transdisciplinary design features and RP abilities. Inventory expense and waste have been decreased because of its ability to facilitate on-demand manufacturing and mass customization [11]. The wide range of polymers that may be utilized with this method has dramatically expanded its potential applications. Thermoplastics designed for use in industry and effective engineering polymers are two examples. AM facilitates autonomous manufacturing and backs environmental initiatives [12]. Less transport is required, which also aids resource management. Each year, new opportunities for product customization and improvement arise from technological advancements in the metal and polymer industries, which, in turn, alter manufacturing standards and methods.

Scopus data reveals significant trends in materials and usage in the present AM environment. There is a 54.8% market share for polymer AM and a 45.2% market share for metal AM. The wide range of industries that use these materials is shown in Fig. 1. For example, 58.5% are used in manufacturing and industry, 20.1% in medicine and dentistry, 12.5% in energy, and 6.8% in consumer goods. The evidence indicates that a significant proportion of researchers are curious about exploring advanced composites, specifically carbon-based nanomaterials, and nano clay (48%). This indicates a significant utilization of AM technologies. Natural fibers (NFs) constitute 11.3% and are gaining popularity as sustainable alternatives.

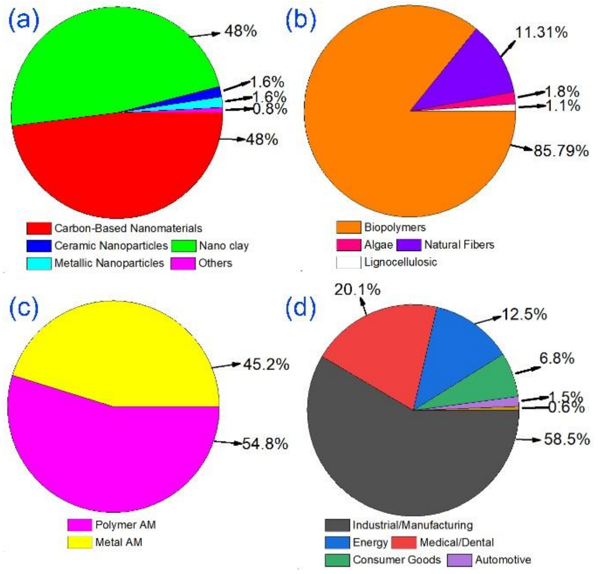

Fig. 1. Scopus: AM view (a) Nanomaterial (b) NFs (c) Market: polymers vs. metals (d) Main sectors

Fig. 2 illustrates the increase in research publications on AM of metals and polymers, providing a precedent for this market segment. Research has progressed significantly, especially since 2015, following a prolonged period of stagnation. There were more papers about metal AM than about polymer AM from 2020 to 2024. This, together with the industry share figures, suggests a significant shift in research focus toward industrial metal technologies in recent years. The initiative aims to capitalize on the growing demand for eco-friendly materials by using NFs derived from biodegradable waste through a new, environmentally friendly method. Data show that biopolymers are becoming more popular (85.7% of the natural materials investigated), and the specific utilization of waste from food, wood, and agriculture as functional fillers represents a compelling frontier. To turn these inexpensive, abundant, and sustainable waste elements into new composite filaments, this study investigates potential recycling processes. This would turn these environmental problems into valuable resources for future generations.

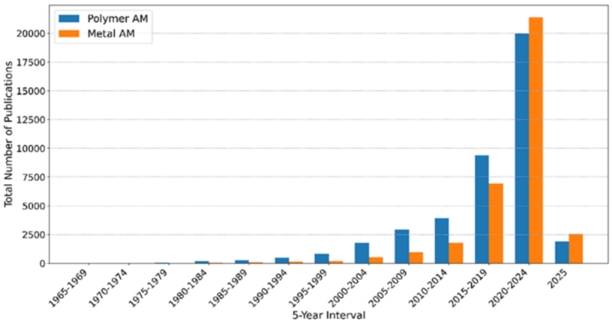

Fig. 2. Growth in metal and polymer AM

By allowing direct, layer-wise production from digital models, AM overcomes the drawbacks of tooling-based, subtraction, and formative techniques. AM compresses development cycles and eliminates non-recurring tooling costs that dominate low-to-medium production volumes. Features that were previously unattainable with conventional methods are now possible with the geometric freedom it enables, delivering higher specific performance, lower mass, and improved thermal and flow management. The digital design process facilitates mass customization, such as personalized patient devices and specialized jigs and fixtures, as well as on-demand, flexible production of limited volumes. These benefits enhance supply-chain resilience and keep inventory at a minimum. The amount of material wasted per part is generally lower than that of subtractive methods, leading to less discarded material and leaving room for circular strategies such as recycling or using pre-recycled materials. In addition, the ability to conduct on-site sensing and computer simulations enhances traceability within digital product development and production systems. AM enhances traditional manufacturing by widening design possibilities, optimizing unit economics where tooling is costly, and expediting the transition to production, resulting in measurable improvements in performance, speed to market, and sustainability.

2. CLASSIFICATION OF AM METHODS

AM encompasses a wide range of techniques for building physical objects by layering materials onto a surface. Fig. 3 shows that these technologies can be categorized in several ways per ASTM committee F42 [13]. Methods that selectively cure liquid photopolymers in a controlled environment using light-activated polymerization are referred to as Vat photopolymerization in the first category. Digital light processing (DLP) and SLA are two of the most well-known examples of this field [14]. The second method is material jetting, which includes multijet modeling and PolyJet, which uses droplet stacking selectively to create materials [15]. Bender jetting is the subsequent category and involves the careful application of a liquid adhesive to combine particles. Materials extrusion methods, including material selection based on nozzles or perforations, constitute the fourth category and are carried out using either fusion filament fabrication (FFF) or FDM [16].

A method that utilizes heat to mix powder beds is known as powder bed fusion. Ultrasonic consolidation and Laminated Object Manufacturing (LOM) are two examples of the sixth class of manufacturing processes. This class contains technologies that combine material strips to make a product. The seventh kind of directed energy deposition (DED) involves applying intense heat to molten or fused solids. Two examples of such methods are direct metal deposition (DMD) and laser engineered net shaping (LENS). Approaches that employ the selective deposition or drying of liquid materials include material jetting and vat photopolymerization [17].

Sheet lamination and material extrusion are two examples of solid-based processes that use melted, extruded, or fused solid materials. Some powder-based techniques, such as binder jetting and PBF, rely on precise melting or bonding of powders [18]. These classifications shed light on the several AM technologies that set them apart. These systems classify AM processes based on energy source, deposition technique, and material type, among other important parameters that consider material attributes, part complexity, and production capacity [19].

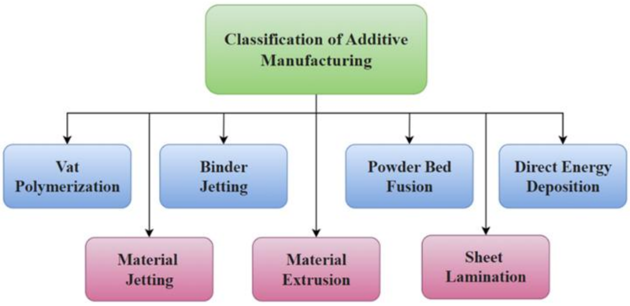

Fig. 3. AM classification [20]

3. POLYMER-BASED AM METHODS

The early days of polymer-based 3D printing have revolutionized several industries, from aerospace and automotive to dentistry and healthcare, and even consumer goods. It allows exceptional levels of creative freedom, personalization, and quick prototyping. Both the extrusion and the vat photopolymerization approaches have benefits and drawbacks, and these technologies are usually classified suitably [21]. Fig. 4 shows the categorization of AM technologies based on polymers, which includes SLS, FDM, DLP, Multi Jet Fusion (MJF), and PolyJet/material jetting. Polymer-AM is a collective term for a wide variety of approaches, each with its own advantages and limitations. Layers of material are deposited layer by layer using FDM, a process based on extrusion, for inexpensive, fast prototyping and educational purposes. The thermoplastic filaments used include acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). From consumer goods to automobile prototypes, achieving surface polish and dimensional accuracy is a significant challenge [16].

One method that uses ultraviolet (UV) rays to form the material into its final, perfectly smooth layers is stereolithography (SLA). This vat photopolymerization technique is excellent for making dental models and jewelry molds. Medical equipment with intricate prototypes often uses it, despite the high material prices and post-processing requirements [22]. DLP, like SLA, cures entire resin layers using a digital projector for faster printing, excelling in small, detailed parts such as hearing aids, but is limited by resin brittleness and material variety, and is commonly adopted in the healthcare and dental sectors [14]. Using a laser, SLS fuses powdered polymers, enabling the creation of intricate geometries on its own, and produces durable aerospace and automotive parts. The equipment costs and powder handling issues are still a big issue, as well as support for small-batch production [6]. MJF is a technique that uses the spreading of polymer powder, applying fusing agents and heat to form isotropic, mechanically robust parts mainly used in the aerospace and automotive industries. This technique, despite the costly setup, produces end-use components such as geometrically specific brackets. PolyJet/Material Jetting jets photopolymer droplets, which are then cured by UV light, providing high-resolution, multi-material parts suitable for medical models as well as consumer goods. They are limited by material costs and slower speeds similar to those used for detailed prototypes [15]. Table 1 presents the comparison among different polymer and metal AM parts.

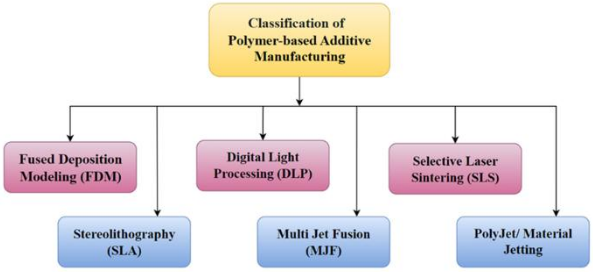

Fig. 4. Polymer-Based AM Categorization [23]

Table 1. Comparison of polymer and metal AM

AM type	Specific strength (Tensile strength/density)	Cost-effectiveness
Polymer: PA12 (SLS)	52 (48 MPa / 0.93)	High
Polymer: PEEK (FFF)	83 (105 MPa / 1.26)	Medium: excellent specific strength but expensive filament
Continuous CF-reinforced nylon	667 (800 MPa / 1.2)	High for lightweight tooling/fixtures
Metal: $AlSi_{10}Mg$ (LPBF)	172 (460 MPa / 2.67)	Medium-Low: post-processing adds cost
Metal: Ti-6Al-4V G5 (LPBF)	250 (1100 MPa / $\geq$4.4)	Low and very high machine + finishing costs
Metal: 316L stainless (LPBF)	75 (600 MPa / $\geq$7.97)	Medium-Low: cheaper powder than Ti

4. FUSED DEPOSITION MODELING

One popular AM technique for making thermoplastic components is FDM (Fused Deposition Modeling, also known as FFF). FDM, created in the '80s by Scott Crump and made into the market by Stratasys [24] in the 1990s. It is widely popular among 3D printing techniques for its ease of use, efficiency, affordability, and versatility. As shown in Fig. 5, the FDM builds 3D structures by sequentially layering thermoplastic material in molten form. From the extruder unit, a nozzle transfers the melted strand to the construction platform. The required three-dimensional form is constructed by extruding the molten material.

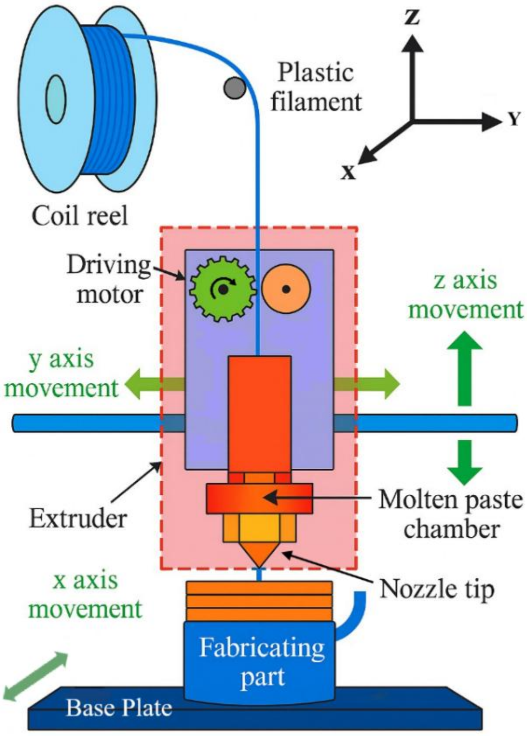

Fig. 5. An illustration of the FDM method [25]

Three primary components make up a filament-dispensing machine (FDM) 3D printer: the heated platform, the print head, and the filament feeding mechanism [26]. To extrude thermoplastic filaments, such as ABS, PLA, or Polyethylene terephthalate glycol (PETG), heated to a plastic state in a semi-solid state [27]. The melted material is deposited onto the printed layer or the platform by means of the print head's nozzle extrusion [28]. Accurate regulation of the printer head's motion and material extrusion is the core idea of FDM. Moving along different axes, the print head follows the geometry of the part's cross-section, while the platform follows the part's Z-axis to accommodate the subsequent layers [29]. Rapid cooling and solidification follow extrusion, allowing the molten material to fuse with neighbouring layers to produce a solid component [30]. Several critical printing parameters affect the mechanical characteristics and general performance of FDM-developed components. These parameters include extrusion speed, layer thickness, raster orientation, and printing temperature. It is crucial to tune these variables to meet the component's functionality and surface integrity criteria [31].

Furthermore, post-processing may allow the elimination of support frames that are necessary for overhanging components. Several fields have discovered uses for FDM, including prototyping, tooling, education, and end-user components [32]. Since it can produce functional components with complex geometries, it finds widespread applications in medicine, aviation, and the automotive industry. Compared with other 3D printing technologies, FDM has several drawbacks, including anisotropic mechanical properties, visible layer lines, and a limited material selection [33].

Ambient humidity and storage discipline are first-order determinants of FDM reliability because many filaments (PA/nylon, PVA, TPU, PEI/PEEK, and, to a lesser extent, PLA) are hygroscopic. They absorb water within hours to days, which then flashes to steam in the hot end, causing popping, bubbles/voids, stringing, surface roughness, and weakened inter-layer bonding that lowers mechanical performance and increases clog/under-extrusion risk [34]. To avoid these failures, vendors recommend sealed storage with desiccant or active dry boxes and limiting ambient exposure; even mainstream guidance notes that keeping spools in a closed, desiccated container is preferable to repeated re-drying. To avoid foamy extrusion and property degradation, high-temperature materials (PEEK/PEI) typically need ≤0.02% moisture. In contrast, Stratasys endorses printing with FDM thermoplastics only when the residual moisture is <0.04%. Part-to-part uniformity and uptime can be improved by managing low relative humidity during printing. This can be achieved using dry boxes, enclosed feed routes, heated/enclosed build chambers, and other similar techniques [35]. Additionally, this helps to preserve the dimensional integrity and surface polish.

5. IMPACT OF AM PROCESS VARIABLES

There is a strong correlation between AM production factors (particularly those related to FDM) and the characteristics, performance, and quality of the finished product. The desired printing effectiveness can be obtained by altering the customizable parameters [36]. It is essential to understand how process parameters affect the mechanical, corrosion, and wear properties of parts so they work reliably and consistently. Building orientation, infill density, printing speed, raster angle, and layer height are among the most critical factors [37]. Stack orientation is an essential part of AM since it influences the strength and precision of the final output. The relative positioning of the various axes on the platform is the key to unlocking optimum printing efficiency in the process. Multiple orientations for the components are shown in Fig. 6.

Numerous features are impacted by the layer thickness, such as the quality of the surface, the build duration, and the precision of the part measurements. Considering the material's flow behaviour, the print temperature affects interlayer bonding and the overall component strength. The cooling period and interlayer adhesion are influenced by the printing rate, which, in turn, is determined by the material deposition rate and the nozzle's motion [38]. Fig. 7 shows the results of the tensile test, which indicate that, for a 0.25 mm thickness, tensile stress and strain are reduced as the printing speed increases (30 to 50 mm/s). Items made with FDM may exhibit better mechanical properties when printed at slower rates, as the maximum tensile stress (26 MPa) was observed at a printing rate of 30 mm/s [39].

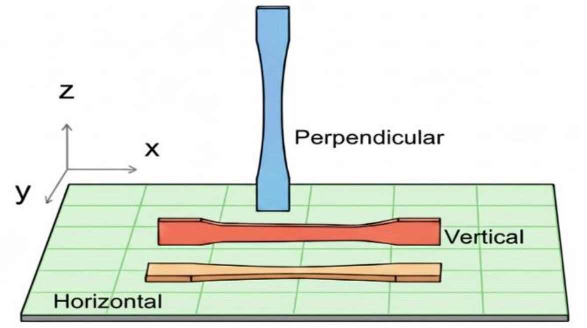

Fig. 6. Build direction in FDM

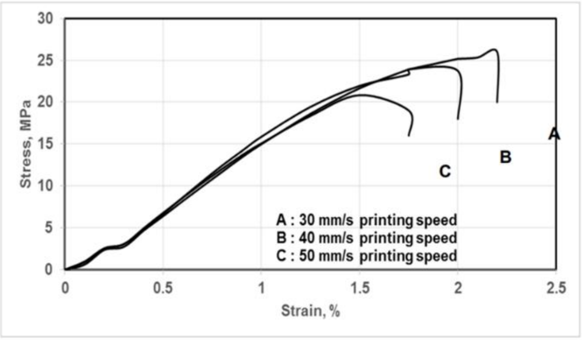

Fig. 7. Stress-strain association at various speeds of printing [39]

The direction of the infill pattern along the print platform's X-axis is the raster angle, which may affect the anisotropic mechanical properties of the printed products. Fig. 8 shows the several raster angles used during printing. Two common arrangements for raster angles are displayed: +45°/-45° and 0°/90°. The material is deposited at 45° angles to the sample's axis in the +45°/-45° configuration, and along the sample's length and breadth in the 0°/90° arrangement. The mechanical properties and behaviour of printed components can be significantly influenced by these raster angle selections [40].

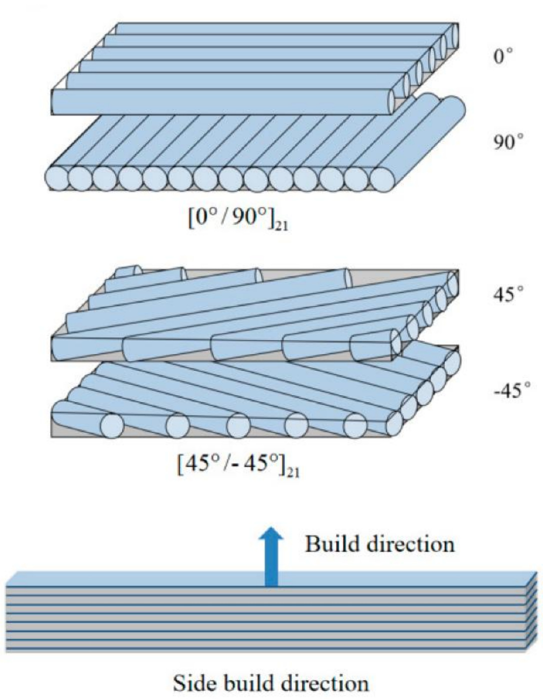

Fig. 8. Layer deposition patterns illustrating different raster angles [40]

The infill material density regulates the component's weight, strength, and rigidity; it is placed within the part. In FDM, researchers explored the effects of layer thickness, deposition angle, and infill on achieving higher flexural strength in parts. The parts' mechanical characteristics were significantly impacted by the angle of deposition and contact with infill; however, the predominant determinant was the thickness of the layer [41]. The impact of different process factors on the mechanical attributes of FDM components was investigated. The elastic modulus and tensile strength of a layer might rise with thickness, while its flexural strength and impact resistance may decrease consequently [42]. Increased printing temperatures can enhance interlayer adhesion and boost ultimate tensile strength; however, excessively high temperatures may lead to material deterioration. Optimizing build orientation, in conjunction with raster angle, can improve mechanical strength and stress distribution [43]. The parts developed through FDM exhibit corrosion and wear resilience, which are influenced by the FDM variables. The load-bearing capacity and reliability of RP model parts were demonstrated by material properties and surface integrity, limiting RP methods to primary design studies and certain substitutes in aerodynamic evaluation [44], even though they offer savings in fabrication time and cost. The ABSP400 parts were evaluated for compressive strength using different combinations of air gap, layer thickness, printing orientation, raster width, and angle. The developed parts demonstrated heterogeneity and brittle characteristics. The final product's toughness is strongly influenced by factors such as interlayer association, molecular arrangement, and the strength of fiber interactions. By optimizing settings, one can maximize compressive stress [45].

6. MECHANICAL CHARACTERISTICS

Mechanical properties are crucial to the significance and durability of FDM-produced goods, which are influenced by a wide range of factors, including printing configurations, processing conditions, and product design. Understanding the mechanical qualities of FDM products is vital to improving the printing process and ensuring the creation of superior, functioning components [46]. The impact, tensile, flexural, and compressive strengths of FDM components are currently the center of substantial research [47]. The flexural strength of a material is a measure of its resistance to bending stress, whereas its tensile strength is a measure of the stress it can endure before breaking under tension [48]. The capacity of a material to resist bending stresses is demonstrated by its flexural strength. The study investigated the effects of various infill patterns on the strength-to-weight ratio and the maximum allowable compressive load. The authors had considered 5 densities and 14 infill pattern approaches [49]. A recent study investigated the tensile strength of ABS-3D-printed parts with various layer thicknesses (Fig. 9), comparing how strength relates to the build direction and to bonding to component strength. Generally, the peak force and tensile strength are maximum in the thicker layer. However, including additional layers will provide a more compact assembly; the interlayer strength is lower than the polymer intermolecular strength [50].

As shown in Fig. 10, the impact strength of 3D-printed components increases with increasing infill proportion, layer thickness, and print speed, but decreases sharply as the extrusion temperature rises. While the impact absorption potential was significantly related to the apparent density, the effect of layer height was not as significant.

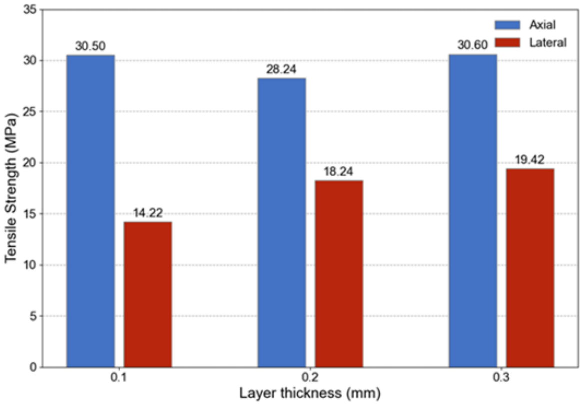

Fig. 9. Tensile strength at various layer thickness [50]

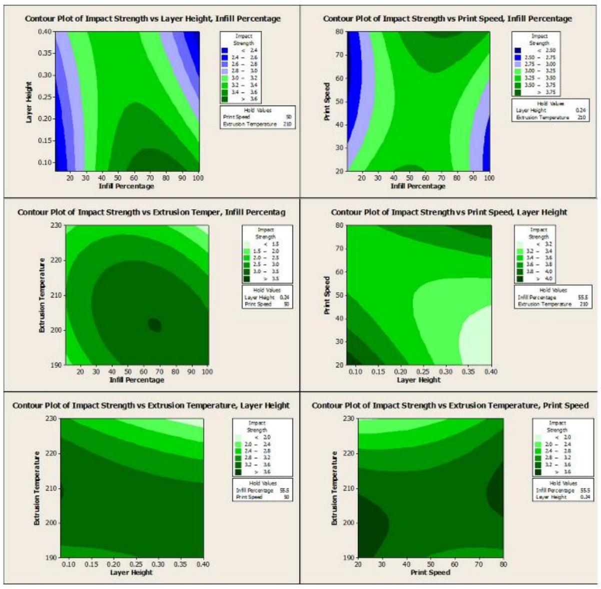

Fig. 10. Process variables effect on the impact strength [51]

The Shore D harness for ABS and PLA samples is shown in Fig. 11, with infill % of 50, 75, and 100 and layer thickness of 0.1, 0.15, and 0.2 mm. The hardness qualities of PLA and ABS, as well as the friction coefficient and cumulative linear wear, follow a clear pattern. Compared to ABS-printed samples, PLA samples have an average hardness that is 28.57% greater. Compared with ABS, PLA has much greater indentation resistance, indicating that it can better resist distortions caused by external forces [52]. Quantitative studies show that solid (100% infill) FDM parts still contain measurable voids and that porosity (ϕ) is a primary predictor of tensile and flexural performance across polymers. Micro-CT (μCT) of nominally dense prints reported ϕ of 0.2% for PLA versus 5.5% for PVA, with the lower-porosity PLA exhibiting correspondingly higher strength, underscoring the sensitivity of properties to even sub-percent voids [53]. In short CF-ABS systems, μCT resolves how processing steps drive ϕ: 7.78% (pellet) to 17.2% (freely extruded strand) to 13.56% (deposited bead) and down to 10.12% with in-situ roller compaction; higher extruder rpm, modestly higher nozzle temperature (220 °C), and lower standoff further decrease void fraction [54].

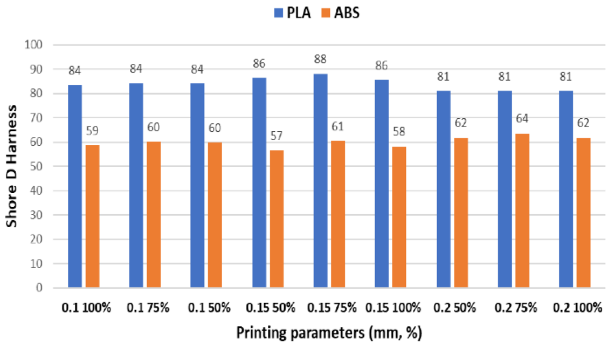

Fig. 11. Shore D hardness of printed samples [52]

At the structural level, increasing intentional porosity (low infill) in short-CF ABS from 13% to 53% produces large drops and higher scatter in tensile strength, while aligning raster (0°) can recover <40% strength relative to ±45° by mitigating inter-bead pores [55]. For PETG, porosity decreases monotonically with increased extrusion, and optimized layer/nozzle combinations reduce both ϕ and inhomogeneity [56]. Raising density (lowering ϕ) yields significant gains in elastic modulus (up to 2.2-fold) and strength (up to 1.5-fold) in small-scale FDM specimens as infill approaches 100% [57]. Studies further attribute tensile losses in ABS to positive air gaps (more voids) and improvements to negative air gaps (bead overlap), reinforcing the porosity-strength correlation; flexural strength in PLA shows the same trend with infill/porosity reduction [29]. For PLA, ABS (and CF-ABS), and PETG, minimizing ϕ via parameter selection (air gap, raster layout, extrusion/temperature, compaction) or post-deposition densification is the most direct route to higher and more repeatable tensile/flexural performance. Table 2 presents the relationships between the different FDM process parameters considered and the properties.

Table 2. Property-parameter relationship

Parameter	Typical setting window	Primary properties	Quantitative effect size
Nozzle temperature	Within ±10-20 °C	Interlayer weld, tensile/flexural strength, porosity	Moderate weld strength. Heat deflection temperature (HDT) rises by 80% 20°C when bed/nozzle elevated appropriately
Bed/chamber temperature	Bed: 50-110 °C; chamber: 40-60 °C (ABS)	Warpage, voids, strength scatter; crystallinity	Rises tensile/impact and reduced warpage; promotes in-situ annealing for semi-crystalline polymers
Layer height	0.10-0.30 mm	Tensile strength/modulus; surface finish	Lower layer height rises tensile stress by 10-70%
Infill density	Infill 20-100%; perimeters 2-6	Tensile stress, Young's modulus	Raising infill toward 100% typically raises tensile strength and modulus by 2-5 fold
Raster angle / build orientation	0°/90°/±45°; X-Y vs Z builds	Anisotropy of fatigue, tensile, and flexural stress	Unfavorable orientation lowers tensile stress by 40-55% (0° to 90°: -44% ABS, -53% PLA)
Print speed	20-120 mm/s (material/geometry dependent)	Weld quality, tensile stress, and accuracy	Higher speed often lowers tensile stress (5-30%) and accuracy

7. THERMAL DEGRADATION MECHANISMS

During FDM, polymers experience short, repeated thermal histories and shear in an oxygenated melt, driving thermo-oxidative chain scission (limited crosslinking) that lowers molecular weight and alters relaxation/crystallization kinetics. In ester-based systems like PLA, trace moisture plus heat promotes hydrolytic scission and transesterification; in ABS, the polybutadiene phase is especially susceptible to oxidation-initiated scission, while Styrene-Acrylonitrile (SAN) embrittles with heat aging. Differential scanning calorimetry (DSC) generally indicates a minor depression in the glass transition temperature (Tg) and alterations in cold-crystallization (Tcc, ΔHcc) and melting characteristics (ΔHm/Tm, occasionally exhibiting double-melting due to reorganization), which are indicative of shorter polymer chains and altered nucleation processes during raster reheating. Thermogravimetric analysis (TGA) typically indicates an earlier onset of mass loss (lower Tonset/Td, 5%) and alterations in Tmax/char compared to the as-received filament. The trends become more pronounced with extended reprocessing and recirculation cycles, as well as increased residence times. Therefore, it is essential to establish a safe processing window by integrating DSC-derived softening and melting characteristics with TGA-derived onset temperatures, while also limiting thermal proximity in the nozzle. The literature on FDM of PLA/ABS consistently reports these and links them to parameter control (nozzle/bed temperatures, speed, cooling) and to part-to-part reheating by adjacent raster and layers [58]. All the filaments studied exhibited a sigmoidal step shift (endothermic), as seen in Fig. 12, which displays the DSC curves of filaments varying in naproxen (NAP) concentration. Extra thermal processes, such as enthalpy restoration and, maybe, moisture evaporation from the 10% NAP, are seen in the image. Glass transition temperature (Tg) indicates that an amorphous solid dispersal was created by means of this binary combination.

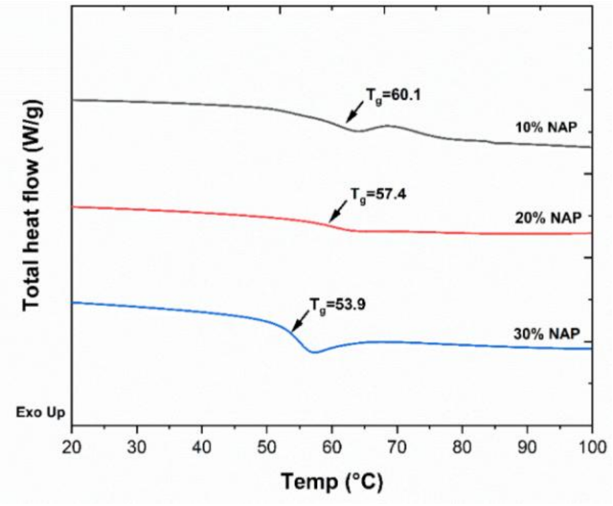

Fig. 12. Filaments Tg with varying NAP [59]

The dry and wet DSC thermograms of wood-PLA and PLA are shown in Fig. 13. The Tg of dry PLA was found to be 58.8°C, suggesting movement of the polymer chains in clean PLA was little affected by the uptake of water. On the other hand, the Tg of dry wood-PLA was 57.2°C and dropped to 55.5°C after moisture absorption.

Fig. 14 shows the thermo-gravimetric analysis (TGA) data, which demonstrate that the primary weight loss for every specimen happened around 300°C and 400°C, which is when the PLA matrix thermally decomposed. The TG and derivative thermogravimetry (DTG) curves in the wet wood-PLA shifted somewhat toward lower temperatures, indicating that the aqueous wood fibers absorbed and held some moisture [60].

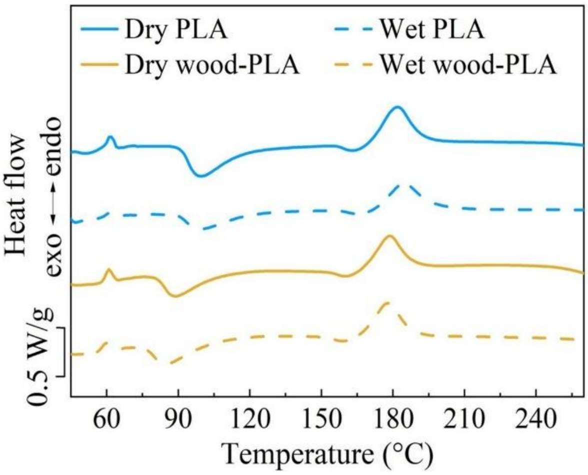

Fig. 13. DSC plot for wood-PLA and PLA [60]

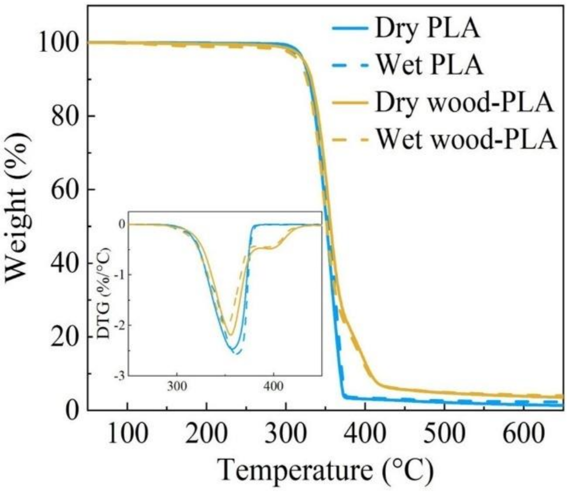

Fig. 14. TGA plots for wood-PLA and PLA [60]

8. CONCLUSIONS

The article examines the transformative capabilities of AM in FDM systems utilizing polymers to create intricate, high-performance components applicable in the fields of medicine, mobility, and aviation. Process variables, including nozzle temperature, build orientation, and layer thickness, influence the microstructure, wear durability, and mechanical properties. The significance of regulating these variables to fulfil their functional requirements is illustrated. In addition to AM's exceptional design freedom, problems with material integrity, process repeatability, and minimal post-processing persist. The addition of nanoparticles to 3D printed things makes them stronger. To tailor mechanical strength and structural integrity in polymer composites, it will be indispensable to consider the interplay among printing variables, material formulations, and the materials themselves. The reviewed literature establishes the foundation for the examination. The idea is to improve the development of robust polymer composites by integrating experimental results with computer simulations to make AM more sustainable for tailored manufacturing.

9. FUTURE SCOPE OF RESEARCH AND LIMITATIONS

Future improvements in polymer AM techniques and materials, as well as 4D printing and the implementation of intelligent polymers, may result in new, never-before-seen parts that can alter their shape in response to various environmental stimuli, such as temperature, light, pH levels, humidity, and more. This may facilitate the development of deployable lattices, self-actuating fixtures, and programmable biomedical equipment capable of executing specific functions. Recent reviews emphasize significant advancements in stimuli-responsive shape-memory systems, 4D processing methods (including vatting, extrusion, and jetting), and the principles governing consistent actuation. Recent developments in vitrimers and other covalently adaptable networks enable the reprocessing, repair, and recycling of printed thermosets, facilitating circular economy approaches while maintaining performance standards. Beyond actuation and sustainability, self-healing and electrically conductive polymers are maturing for Fused Filament Fabrication (FFF) and Direct Ink Writing (DIW), as well as photopolymer routes, pointing to embedded electronics, soft-robotic skins, and damage-tolerant structural skins. From a processing perspective, ML-assisted, in-situ-monitored printing (closed-loop control with thermal/vision/acoustic sensing) shows great promise in taming defects and improving lot—to—lot reliability. Volumetric AM (VAM) and continuous additive lithography (CAL) offer layer-free, second-scale builds for complex shapes using photopolymers. The review presented in this article is constrained by a heterogeneous literature that mainly focuses on altering process variables and their impact, severely limiting direct cross-study comparisons. The effect of reinforcements such as particulates, biofillers, and fibers is not considered, which may be targeted in future studies. Thermal thresholds often derive from inert-atmosphere TGA/DSC, whereas printing occurs in air, complicating inferences about degradation. Findings on nano-filled and continuous-fiber filaments depend on proprietary formulations and small, non-transferable ML datasets. Simulation studies of 3D-printed parts are not considered in this review and can be addressed in the future.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] A. Jandyal, I. Chaturvedi, I. Wazir, A. Raina, M.I. Ul Haq, 3D printing – A review of processes, materials and applications in industry 4.0. *Sustainable Operations and Computers*, 3, 2022: 33–42. https://doi.org/10.1016/j.susoc.2021.09.004

[2] R. Kumar, M. Kumar, J.S. Chohan, Material-specific properties and applications of additive manufacturing techniques: a comprehensive review. *Bulletin of Materials Science*, 44, 2021: 181. https://doi.org/10.1007/s12034-021-02364-y

[3] D. Wyszynski, M. Grabowski, Chapter 9-Powder bed fusion, in: Polymers for 3D Printing. *William Andrew Publishing*, 2022: 105–112. https://doi.org/10.1016/B978-0-12-818311-3.00001-X

[4] M. Galati, Chapter 8 - Electron beam melting process: a general overview, in: Additive Manufacturing. *Elsevier*, 2021: 277-301. https://doi.org/10.1016/B978-0-12-818411-0.00014-8

[5] H.K. Dave, J.P. Davim, Fused Deposition Modeling Based 3D Printing. *Springer International Publishing*, Switzerland, 2021.

[6] E. Yasa, Chapter 3 - Selective laser melting: principles and surface quality, *Additive Manufacturing*. *Elsevier*, 2021, pp. 77-120. https://doi.org/10.1016/B978-0-12-818411-0.00017-3

[7] A. Kafle, E. Luis, R. Silwal, H.M. Pan, P.L. Shrestha, A.K. Bastola, 3D/4D Printing of Polymers: Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA). *Polymers*, 13(18), 2021: 3101. https://doi.org/10.3390/polym13183101

[8] I. Gibson, D. Rosen, B. Stucker, M. Khorasani, Additive Manufacturing Technologies, Third Ed., *Springer International Publishing*, Switzerland, 2021.

[9] M.K. Thompson, G. Moroni, T. Vaneker, G. Fadel, R.I. Campbell, I. Gibson, A. Bernard, J. Schulz, P. Graf, B. Ahuja, F. Martina, Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals*, 65(2), 2016: 737-760. https://doi.org/10.1016/j.cirp.2016.05.004

[10] M. Kouhi, I.J. de Souza Araújo, F. Asa'ad, L. Zeenat, S.S.R. Bojedla, F. Pati, A. Zolfagharian, D.C. Watts, M.C. Bottino, M. Bodaghi, Recent advances in additive manufacturing of patient-specific devices for dental and maxillofacial rehabilitation. *Dental Materials*, 40(4), 2024: 700-715. https://doi.org/10.1016/j.dental.2024.02.006

[11] J.W. Stansbury, M.J. Idacavage, 3D printing with polymers: Challenges among expanding options and opportunities. *Dental Materials*, 32(1), 2016: 54-64. https://doi.org/10.1016/j.dental.2015.09.018

[12] S. Ford, M. Despeisse, Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, 137, 2016: 1573-1587. https://doi.org/10.1016/j.jclepro.2016.04.150

[13] D.L. Bourell, T. Wohlers, Introduction to Additive Manufacturing, in: Additive Manufacturing Processes. *ASM International*, 24, 2020: 3-10. https://doi.org/10.31399/asm.hb.v24.a0006555

[14] R. Magazine, B. van Bochove, S. Borandeh, J. Seppälä, 3D inkjet-printing of photo-crosslinkable resins for microlens fabrication. *Additive Manufacturing*, 50, 2022: 102534. https://doi.org/10.1016/j.addma.2021.102534

[15] M. Vaezi, H. Seitz, S. Yang, A review on 3D micro-additive manufacturing technologies. *The International Journal of Advanced Manufacturing Technology*, 67, 2013: 1721-1754. https://doi.org/10.1007/s00170-012-4605-2

[16] B.N. Turner, R. Strong, S.A. Gold, A review of melt extrusion additive manufacturing processes: I. Process design and modeling. *Rapid Prototyping Journal*, 20(3), 2014: 192-204. https://doi.org/10.1108/RPJ-01-2013-0012

[17] A. Mostafaei, A.M. Elliott, J.E. Barnes, F. Li, W. Tan, C.L. Cramer, P. Nandwana, M. Chmielus, Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. *Progress in Materials Science*, 119, 2021: 100707. https://doi.org/10.1016/j.pmatsci.2020.100707

[18] J.-P. Kruth, G. Levy, F. Klocke, T.H.C. Childs, Consolidation phenomena in laser and powder-bed based layered manufacturing. *CIRP Annals*, 56(2), 2007: 730-759. https://doi.org/10.1016/j.cirp.2007.10.004

[19] N. Guo, M.C. Leu, Additive manufacturing: technology, applications and research needs. *Frontiers of Mechanical Engineering*, 8, 2013: 215-243. https://doi.org/10.1007/s11465-013-0248-8

[20] S.S. Alghamdi, S. John, N. Roy Choudhury, N.K. Dutta, Additive Manufacturing of Polymer Materials: Progress, Promise and Challenges. *Polymers*, 13(5), 2021: 753. https://doi.org/10.3390/polym13050753

[21] J. M. Costa, E. W. Sequeiros, D. Figueiredo, A. R. Reis, M. F. Vieira, Optimizing Metal AM Potential through DfAM: Design, Performance, and Industrial Impact, in: Additive Manufacturing - Present and Sustainable Future, Materials and Applications. *IntechOpen*, 2024. https://doi.org/10.5772/intechopen.1007309

[22] K. Salonitis, 10.03 - Stereolithography, Comprehensive Materials Processing. *Elsevier*, 10, 2014: 19-67. https://doi.org/10.1016/B978-0-08-096532-1.01001-3

[23] Y.W. Adugna, A.D. Akessa, H.G. Lemu, Overview study on challenges of additive manufacturing for a healthcare application. *IOP Conference Series: Materials Science and Engineering*, 1201, 2021: 012041. https://doi.org/10.1088/1757-899X/1201/1/012041

[24] S. Aghajani, C. Wu, Q. Li, J. Fang, Additively manufactured composite lattices: A state-of-the-art review on fabrications, architectures, constituent materials, mechanical properties, and future directions. *Thin-Walled Structures*, 197, 2024: 111539. https://doi.org/10.1016/j.tws.2023.111539

[25] P.I. Anakhu, C.A. Bolu, A.A. Abioye, J. Azeta, Fused Deposition Modeling Printed Patterns for Sand Casting in a Nigerian Foundry: A

Review. *International Journal of Applied Engineering Research*, 13(7), 2018: 5113-5119.

[26] L.T. Temane, J.T. Orasugh, S.S. Ray, Polymer Additive Manufacturing: An Overview, in: Reference Module in Materials Science and Materials Engineering. *Elsevier*, 2024. https://doi.org/10.1016/B978-0-323-95486-0.00037-5

[27] X. Wang, M. Jiang, Z. Zhou, J. Gou, D. Hui, 3D printing of polymer matrix composites: A review and prospective. *Composites Part B: Engineering*, 110, 2017: 442-458. https://doi.org/10.1016/j.compositesb.2016.11.034

[28] D. Popescu, A. Zapciu, C. Amza, F. Baciu, R. Marinescu, FDM process parameters influence over the mechanical properties of polymer specimens: A review, Polymer Testing, 69 2018: 157–166. https://doi.org/10.1016/j.polymertesting.2018.05.020

[29] S.-H. Ahn, M. Montero, D. Odell, S. Roundy, P.K. Wright, Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, 8(4), 2002: 248-257. https://doi.org/10.1108/13552540210441166

[30] C. Bellehumeur, L. Li, Q. Sun, P. Gu, Modeling of Bond Formation Between Polymer Filaments in the Fused Deposition Modeling Process. *Journal of Manufacturing Processes*, 6(2), 2004: 170-178. https://doi.org/10.1016/S1526-6125(04)70071-7

[31] A. Lanzotti, M. Grasso, G. Staiano, M. Martorelli, The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer. *Rapid Prototyping Journal*, 21, 2015: 604-617. https://doi.org/10.1108/RPJ-09-2014-0135

[32] B. Brenken, E. Barocio, A. Favaloro, V. Kunc, R.B. Pipes, Fused filament fabrication of fiber-reinforced polymers: A review. *Additive Manufacturing*, 21, 2018: 1-16. https://doi.org/10.1016/j.addma.2018.01.002

[33] O.A. Mohamed, S.H. Masood, J.L. Bhowmik, Optimization of fused deposition modeling process parameters: a review of current research and prospects. *Advances in Manufacturing*, 3, 2015: 42-53. https://doi.org/10.1007/s40436-014-0097-7

[34] H. Gong, M. Runzi, Z. Wang, L. Wu, Y. Zhang, Influence of Filament Moisture on 3D Printing Nylon. *Technologies*, 13(8), 2025: 376. https://doi.org/10.3390/technologies13080376

[35] S. Wickramasinghe, T. Do, P. Tran, FDM-Based 3D Printing of Polymer and Associated Composite: A Review on Mechanical Properties, Defects and Treatments. *Polymers*, 12(7), 2020: 1529. https://doi.org/10.3390/polym12071529

[36] J. Zhang, X.Z. Wang, W.W. Yu, Y.H. Deng, Numerical investigation of the influence of process conditions on the temperature variation in fused deposition modeling. *Materials & Design*, 130, 2017: 59-68. https://doi.org/10.1016/j.matdes.2017.05.040

[37] V. Alagumalai, V. Shanmugam, P. Thamizhvalavan, T. Murugaiyan, Effect of infill structures on compressive properties of additively manufactured nylon carbon fibre composite cylinders. *Journal of Reinforced Plastics and Composites*, 2025. https://doi.org/10.1177/07316844251332323

[38] A. Peng, X. Xiao, R. Yue, Process parameter optimization for fused deposition modeling using response surface methodology combined with fuzzy inference system. *The International Journal of Advanced Manufacturing Technology*, 73, 2014: 87-100. https://doi.org/10.1007/s00170-014-5796-5

[39] K.G.J. Christiyan, U. Chandrasekhar, K. Venkateswarlu, A study on the influence of process parameters on the Mechanical Properties of 3D printed ABS composite. *IOP Conference Series: Materials Science and Engineering*, 114, 2016: 012109. https://doi.org/10.1088/1757-899X/114/1/012109

[40] K. Wang, S. Li, Y. Rao, Y. Wu, Y. Peng, S. Yao, H. Zhang, S. Ahzi. Flexure Behaviors of ABS-Based Composites Containing Carbon and Kevlar Fibers by Material Extrusion 3D Printing. *Polymers*, 11(11), 2019: 1878. https://doi.org/10.3390/polym11111878

[41] F. Behlau, M. Thiele, P. Maack, C. Esen, A. Ostendorf, Layer thickness controlling in Direct Energy Deposition process by adjusting the powder flow rate. *Procedia CIRP*, 111, 2022: 330-334. https://doi.org/10.1016/j.procir.2022.08.033

[42] W.A. Khan, M. Hassan, I. Ahmed, M. Xiao, M.I. Faraz, K. Li, I. Khan, R. Muhammad, H. Wu, G. Hussain, Insights into flexural and impact properties of polymer based materials printed through fused filament fabrication: Progress in the last decade. *International Journal of*

Lightweight Materials and Manufacture, 7(6), 2024: 925-957. https://doi.org/10.1016/j.ijlmm.2024.05.011

[43] A.W. Gebisa, H.G. Lemu, Investigating Effects of Fused-Deposition Modeling (FDM) Processing Parameters on Flexural Properties of ULTEM 9085 using Designed Experiment. *Materials*, 11(4), 2018: 500. https://doi.org/10.3390/ma11040500

[44] Z. Zhang, X. Gao, Polypropylene Random Copolymer Based Composite Used for Fused Filament Fabrication: Printability and Properties. *Polymers*, 14(6), 2022: 1106. https://doi.org/10.3390/polym14061106

[45] A.K. Sood, R.K. Ohdar, S.S. Mahapatra, Experimental investigation and empirical modelling of FDM process for compressive strength improvement. *Journal of Advanced Research*, 3(1), 2012: 81-90. https://doi.org/10.1016/j.jare.2011.05.001

[46] J.R.C. Dizon, A.H. Espera Jr, Q. Chen, R.C. Advincula, Mechanical characterization of 3D-printed polymers. *Additive Manufacturing*, 20, 2018: 44-67. https://doi.org/10.1016/j.addma.2017.12.002

[47] M. Balasubramanian, R. Saravanan, Y.-L. Yang, T. Sathish, V. Shanmugam, Exploring the synergistic influence of FDM parameters and strain rate on tensile strength and failure mechanism of FDM printed PLA. *Progress in Additive Manufacturing*, 10, 2025: 2765-2774. https://doi.org/10.1007/s40964-024-00782-y

[48] B. Rankouhi, S. Javadpour, F. Delfanian, T. Letcher, Failure Analysis and Mechanical Characterization of 3D Printed ABS With Respect to Layer Thickness and Orientation. *Journal of Failure Analysis and Prevention*, 16, 2016: 467-481. https://doi.org/10.1007/s11668-016-0113-2

[49] B. Pernet, J.K. Nagel, H. Zhang, Compressive Strength Assessment of 3D Printing Infill Patterns. *Procedia CIRP*, 105, 2022: 682-687. https://doi.org/10.1016/j.procir.2022.02.114

[50] S.T. Dwiyati, A. Kholil, R. Riyadi, S.E. Putra, Influence of layer thickness and 3D printing direction on tensile properties of ABS material. *Journal of Physics: Conference Series*, 1402, 2019: 066014. https://doi.org/10.1088/1742-6596/1402/6/066014

[51] V.S. Jatti, M.S. Sapre, A.V. Jatti, N.K. Khedkar, V.S. Jatti, Mechanical Properties of 3D-Printed Components Using Fused Deposition Modeling: Optimization Using the Desirability Approach and Machine Learning Regressor. *Applied System Innovation*, 5(6), 2022: 112. https://doi.org/10.3390/asi5060112

[52] A.I. Portoacă, R.G. Ripeanu, A. Diniță, M. Tănase, Optimization of 3D Printing Parameters for Enhanced Surface Quality and Wear Resistance. *Polymers*, 15(16), 2023: 3419. https://doi.org/10.3390/polym15163419

[53] D. Markl, J.A. Zeitler, C. Rasch, M.H. Michaelsen, A. Müllertz, J. Rantanen, T. Rades, J. Bøtker, Analysis of 3D Prints by X-ray Computed Microtomography and Terahertz Pulsed Imaging. *Pharmaceutical Research*, 34, 2017: 1037-1052. https://doi.org/10.1007/s11095-016-2083-1

[54] N. Sayah, D.E. Smith, Effect of Process Parameters on Void Distribution, Volume Fraction, and Sphericity within the Bead Microstructure of Large-Area Additive Manufacturing Polymer Composites. *Polymers*, 14(23), 2022: 5107. https://doi.org/10.3390/polym14235107

[55] Ö. Keleş, E.H. Anderson, J. Huynh, J. Gelb, J. Freund, A. Karakoç, Stochastic fracture of additively manufactured porous composites. *Scientific Reports*, 8, 2018: 15437. https://doi.org/10.1038/s41598-018-33863-4

[56] M. Naftaly, G. Savvides, F. Alshareef, P. Flanigan, G. Lui, M. Florescu, R.A. Mullen, Non-Destructive Porosity Measurements of 3D Printed Polymer by Terahertz Time-Domain Spectroscopy. *Applied Sciences*, 12(2), 2022: 927. https://doi.org/10.3390/app12020927

[57] X. Wang, L. Zhao, J.Y.H. Fuh, H.P. Lee, Effect of Porosity on Mechanical Properties of 3D Printed Polymers: Experiments and Micromechanical Modeling Based on X-ray Computed Tomography Analysis. *Polymers*, 11(7), 2019: 1154. https://doi.org/10.3390/polym11071154

[58] V. Shanmugam, K. Babu, G. Kannan, R.A. Mensah, S.K. Samantaray, O. Das, The thermal properties of FDM printed polymeric materials: A review. *Polymer Degradation and Stability*, 228, 2024: 110902. https://doi.org/10.1016/j.polymdegradstab.2024.110902

[59] E.O. Kissi, R. Nilsson, L.P. Nogueira, A. Larsson, I. Tho, Influence of Drug Load on the Printability and Solid-State Properties of 3D-Printed Naproxen-Based Amorphous Solid Dispersion. *Molecules*, 26(15), 2021: 4492.

https://doi.org/10.3390/molecules26154492

[60] W. Xu, M. Li, Y. Xu, A. Entezari, J. Fang, Mechanical Characterization of Fused Deposition Modeling-Printed Wood-Polylactic Acid Composites Under Water Conditioning. *Polymer Composites*, 2025: 1-17. https://doi.org/10.1002/pc.70484