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Influence of Additive Manufacturing Process on the Fatigue of Polymer Materials: A Review

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Abstract
Rapid prototyping has given way to the creation of useful end-use components using Additive Manufacturing (AM), also referred to as three-dimensional (3D) printing. However, the intrinsic layer-by-layer fabrication process results in anisotropic mechanical characteristics and structural flaws that greatly influence the fatigue life of polymer materials. Different parameters affect the fatigue life of a polymer material and subsequently their mechanical properties. In this review, AM process parameters such as build orientation, raster angle, layer thickness and material used are examined, the proper selection of process parameters has an overall impact on the strength of 3D-printed components. This paper offers insights into these process parameters by summarizing recently reported research.

Keywords: *Additive Manufacturing, 3D printing, Polymers, Fatigue Life, and Process parameters.*

1.0 Introduction

Additive manufacturing is a layer-based manufacturing process which allows automatic fabrication of products which enables the automated, cost-effective, and time-efficient manufacture of complexly shaped goods. In the last decade, the application of additive manufacturing has grown significantly, mainly due to the availability of comparatively cheap 3D-printing devices [1]. A process where physical parts are manufactured using computer-aided design (CAD) software and objects are built on a layer-by-layer basis is known as additive manufacturing (AM), or, in a non-technical context, 3D printing [2]. There are different types of AM techniques depending on the feed stock form (e.g., powder versus wire), feeding system (e.g., powder bed versus blown powder), energy source (e.g., laser versus electron beam), materials (e.g., metal versus polymer), etc. [3]. Despite the relatively young age of AM there is a number of studies dedicated to fatigue.

So far, and based on a review by Gülcan et al. [4] the main target applications of parts printed on commercial 3D printers are restricted to color models and applications that are not subject to heavy loads such as moulds used for prototyping purposes. However, the concept of 'additive' manufacturing has originated and evolved significantly [5]. Therefore, the durability and long-term dependability of materials in a variety of developing applications requires an understanding of the fatigue behavior of polymer materials and its damage mechanisms [6]. The core issue is that AM polymers cannot be evaluated as simple isotropic materials, this is because the layer-by-layer fabrication process introduces an unavoidable network of internal anisotropic interfaces, air voids, and surface roughness profiles that alter the mechanics of crack nucleation and propagation which leads to eventual failure under fatigue. Printing parameters have a significant impact on fatigue behaviour that need to be optimized but studies related to the optimization of printing parameters are rare. Rouf et al [7] discusses the various ways in which 3D printing is used to manufacture industrial products, the various process parameters involved in each process, and how they affect the mechanical properties of these parts, such as fatigue, tensile, and bending strength, among others, with a focus on polymeric materials. The static tensile metrics of printed thermoplastics fatigue limits remain highly unpredictable due to the effects, which are inherent in layer-by-layer fabrication processes. These structural defects bypass the typical crack nucleation phase and cause immediate, direction-dependent crack propagation that severely compromises the structural integrity of the component. Hence, further investigations are required [8].

The primary objective of this review is to review the influence of fatigue in 3D printed polymer materials based on the recently reported work in this field given the growing deployment of AM polymer components in sectors like aerospace and automotive engineering where safety is critical. Characterizing their fatigue performance is vital for mitigating premature structural failure. Therefore, a comprehensive understanding of these cyclic failure mechanisms is essential to elevate the structural reliability and durability of printed components where human lives are at stake. The scope of the present study is systematically restricted to Fused Filament Fabrication (FFF) which is extrusion- based and powder-bed Selective Laser Sintering (SLS), this enables a comparative assessment across amorphous, and semi-crystalline materials.

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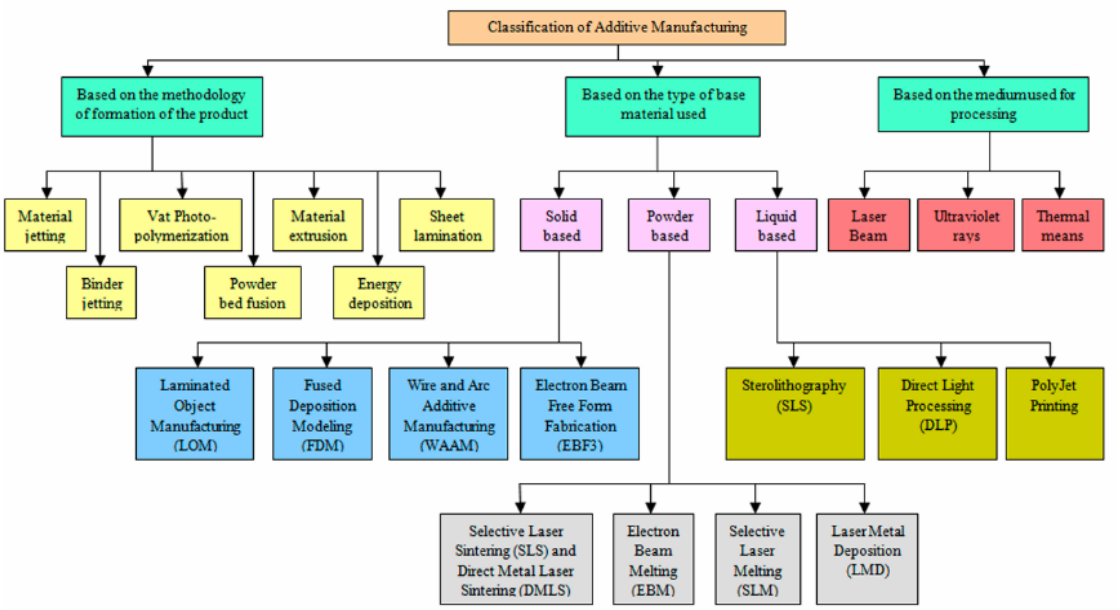

Figure 1: AM processes classified into three main groups

1.1 Classification According to the Method of Fabrication

According to American Society for Testing and Materials (ASTM), AM processes can be classified into the following seven types, based on the methodology of formation of the final components. These are: (1) material extrusion, (2) powder bed fusion, (3) vat photopolymerization, (4) energy deposition, (5) material jetting, (6) binder jetting and (7) sheet lamination [9].

Table 1: Key characteristics of AM processes based on mode of fabrication

Method of fabrication	Key Characteristics	Reference
Material Extrusion (MEX)	Highly accessible and cost-effective; inherently introduces directional anisotropy and distinct layer lines.	[10] [11]
Powder Bed Fusion (PBF)	High structural integrity; SLS polymers do not require support structures because the surrounding unfused powder acts as a natural matrix.	[11, 12]
Vat Photopolymerization (VPP)	Offers exceptional surface finish and high dimensional accuracy (ideal for micro-features); parts can be brittle and prone to UV degradation over time.	[11-13]
Directed Energy Deposition (DED)	Primarily used for high-rate metal deposition, repairing large complex components, or cladding features onto existing conventionally machined structures.	[11, 14, 15]
Material Jetting (MJ)	Capable of multi-material and multi-color printing within a single layer; yields high resolution but lower mechanical/functional durability.	[11, 12, 16]
Binder Jetting (BJT)	Exceptionally fast build speeds and no thermal distortion during printing; metal/ceramic parts require secondary furnace sintering and infiltration to reach full density.	[2, 11, 17, 18]
Sheet Lamination (SL)	Low thermal distortion and high production speed for large volumetric parts; internal complex geometries can be difficult to clear of excess material.	[2, 11, 19]

The creation of polymeric materials has allowed them to be used in many different structural and load-bearing roles, like cams, gears, and mechanical couplings. However, these parts might fracture and fail due to repeated loading (cyclic stress), which could cause a serious accident [20]. This observation is important when thinking about how to design, model, and make components [21].

2.0 Process Parameters Influencing Fatigue of AM Polymer Materials

2.1 Build Orientation and Anisotropy

This is the way a part is positioned during printing, compared to the build plate, and it determines how the layers connect and how they react to outside forces. Build orientation is divided into three setups:

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a) Flat-Horizontal (XY-print): The biggest part of the component lies flat on the build platform. Layers are added along the axis of shorter thickness.

b) On-Edge (XZ-print): The part is turned 90∘ around its long axis, and the layers are built up along the width direction.

c) Vertical-Upright (Z-print): The part is standing straight up, with each layer being added one after the other along its length.

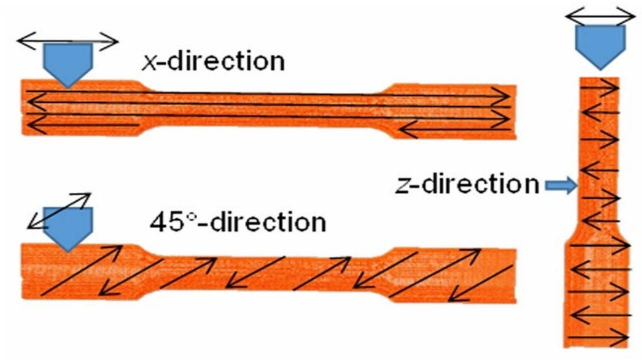

Figure 2: Schematic by Zeltmann et al. [21] showing the orientations of specimens tested for print direction alteration.

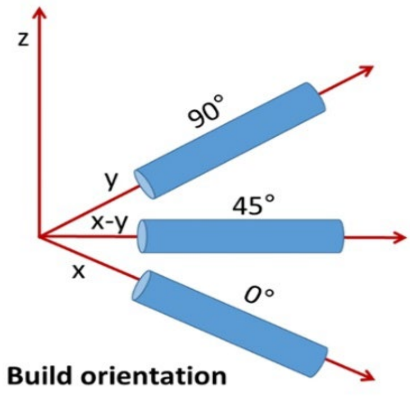

Figure 3: Build orientation

2.2 Raster Angle

Raster angle or degree can be defined as the angle used by the nozzle to lay down melted thermoplastic material in a line by line manner for each layer, and this angle can be set between 0 and 180 degrees [22]. Also, the raster angle is a key factor that influences the compressive strength of FFF printed parts. As the raster angle gets larger, both the ultimate tensile stress and the elastic modulus decrease until the angle reaches 90°. Kumar et al. [23] experimental results showed that the shrinkage in the Z direction is more than in the X and Y directions which happens because the layers compact differently both across and within each layer.

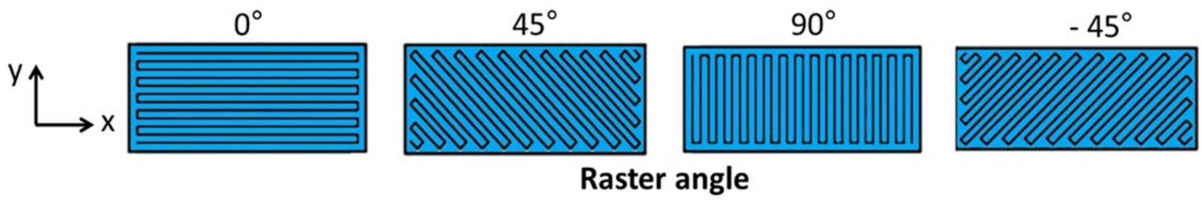

Figure 4: Image showing major raster angles

2.3 Layer Thickness

Thinner layers often improve surface finish, although their effect on fatigue is complex. Smaller layer heights increase the number of interfaces (and potential defect sites) per unit volume. However, they also promote better heat retention and diffusion between layers, potentially enhancing fusion. Voids—unfilled spaces between adjacent raster—act as internal notches. Studies show that reducing void volume through optimized extrusion multipliers can increase fatigue life by several orders of magnitude.

2.4 Material Used in AM Processes

Jafferson and Chatterjee [24] provided an extensive classification of polymeric materials utilized across various additive manufacturing systems, Additive manufacturing uses different techniques to create parts based on the type of material being used and the final product needed. There is a wide range of polymeric materials that are classified into different categories depending on their application in these manufacturing systems. Therefore, depending on what's needed in different industries, FFF technology uses a variety of materials like nylons (NY), acrylonitrile/butadiene/styrene copolymer (ABS), polylactide or polylactic acid (PLA), and even materials that have been mixed with wood or metal powders [25]

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Table 2: Fabrication methods and materials used

Fabrication Method	Materials Used	References
Material Extrusion (MEX)	Thermoplastics (PLA, ABS, PETG, PEEK), continuous fiber-reinforced composites, clays, and hydrogels.	[26,27]
Powder Bed Fusion (PBF)	Thermoplastic powders (PA11, PA12), metal alloys (Titanium, Copper, Steel, Inconel, Aluminum).	[28,29]
Vat Photopolymerization (VPP)	Ceramics, Liquid photopolymer resins (epoxies, acrylates, elastomeric/rigid formulations).	[30,31]
Directed Energy Deposition (DED)	Metal powders or wires (Titanium, Nickel alloys, Stainless steel).	[32,33]
Material Jetting (MJ)	Liquid photopolymer resins, specialized waxes.	[16,34]
Binder Jetting (BJT)	Sand, ceramics, metals (Stainless steel, Copper), gypsum.	[35,36]
Sheet Lamination (SL)	Paper, plastic sheets, metal foils/tapes.	[37]

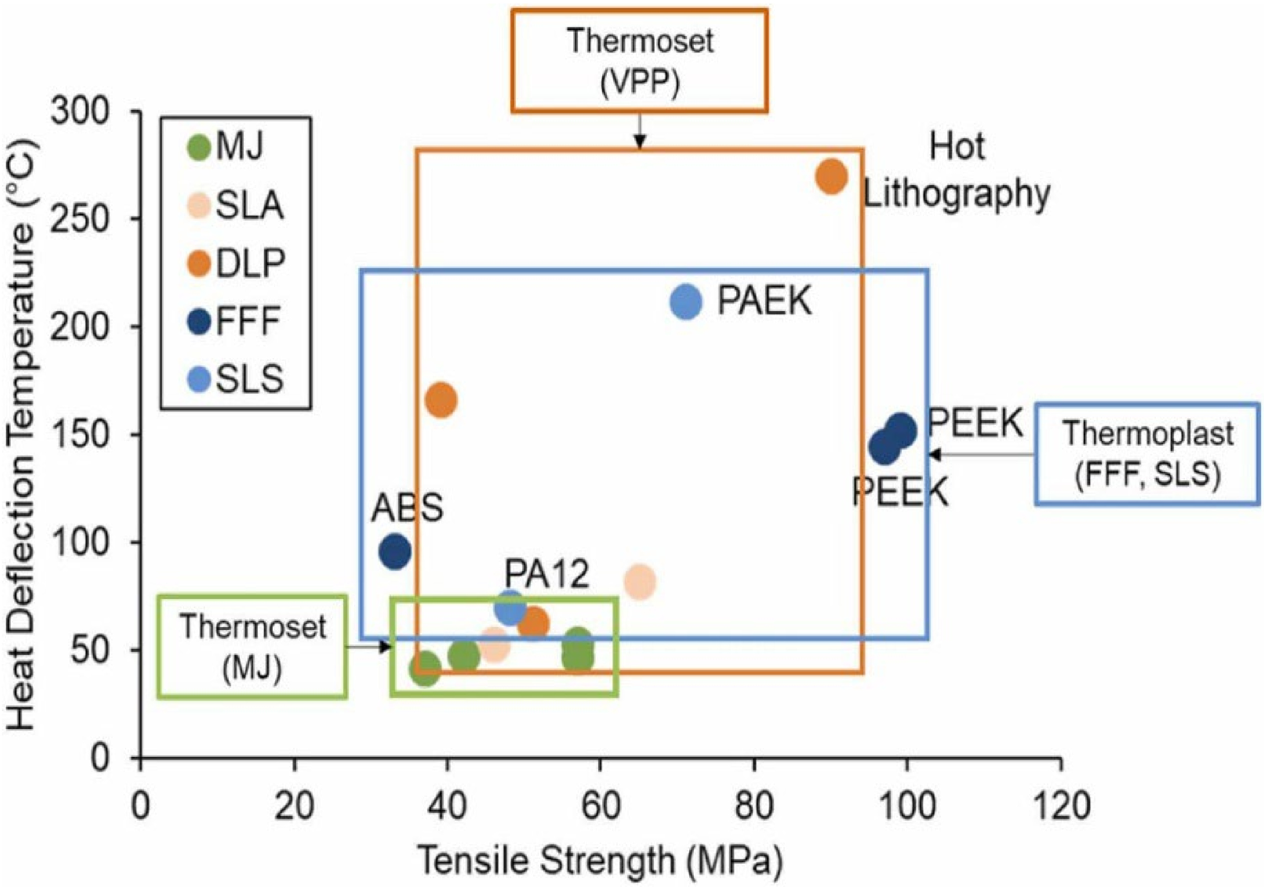

Figure 5: Types of polymer materials used in AM [24]

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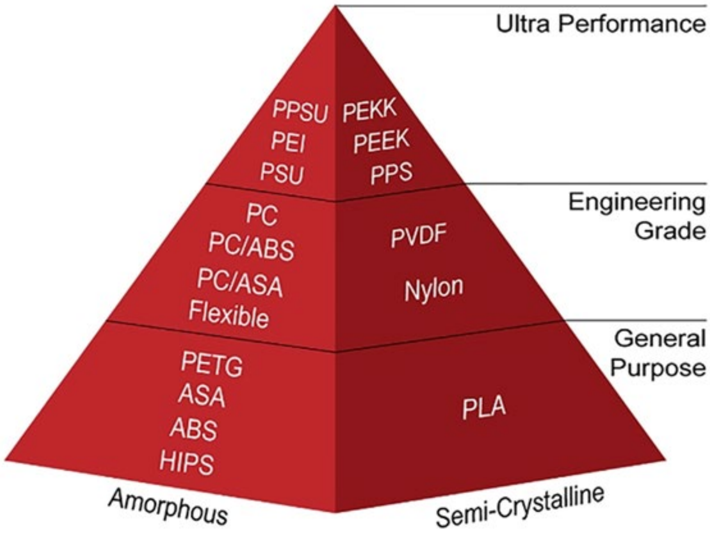

Figure 6: Mechanical and thermal properties of various plastic materials used for various additive manufacturing technologies (material jetting (MJ), stereolithography (SLA), digital light processing (DLP), fused filament fabrication (FFF) and selective laser sintering (SLS)) [16]

3.1 Summary of Key Findings Correlating Process Parameters and Fatigue Properties of AM Polymer Materials

3.1.1 Effect of Build Orientation

Letcher et al [38], showed that by changing the way parts are printed in Polylactic Acid (PLA) on a basic 3D printer, the mechanical strength, like the ultimate tensile strength, can be improved, and this was determined by testing the samples printed in three different directions: 0°, 45°, and 90°, to see how they performed under load. When the orientation changes from 0° to 90°, the material fails in a different way, shifting from ductile to brittle. This change in how the material breaks is mostly because of the direction in which the layers were deposited on the build plate [39]. Similarly, in this field of study, Farzadi et al [40] found that the direction or orientation plays a role in how well plaster-based powder and a water-based solution with 2-Pyrrolidone as a binder work together.

3.1.2 Effect of Raster Angle

By changing the raster angle, Goh et al [22], discovered that the tensile yield strength of the XYZ specimens decreased from 34.5 MPa to 21.3 MPa and then to 20.8 MPa when the raster angle was changed from 0 to 45 and then to 90. This indicates that raster angle changes have an impact on how load is transferred within the specimen because 0° and 45° angles lead to higher fatigue strength. This assertion is corroborated by Shanmugam et al. [6], who found through experimentation that PLA and ABS-based printed materials had a longer fatigue life when the raster angle is oriented at +45° or -45°.

In the research conducted by Zeltmann et al [21], It was discovered that the printing orientation had an impact on the mechanical characteristics of the 3D-printed test coupons. The x and 45° specimens were found to have a modulus that is 36% and 15% greater, respectively, than the z-direction orientation. Furthermore, compared to the z-direction specimens, the strength values of the x and 45° specimens are 28% and 30% greater, respectively. The experiment later done by Azadi et al [41] gives similar results being that the specimen with the 90° direction exhibited the least amount of resistance. The specimen with the 45° direction, however, had the maximum fatigue endurance limit. According to these findings, the optimal printing orientation out of the three is 45°.

Khosravani et al [42] looked into and studied how 3D-printed polymer parts break apart. Samples were printed in three different directions (0, 45, and 90 degrees) to observe how each direction influenced the way the parts failed. The strength and structure of the samples were checked through experiments that measured how much force they could take before fracture and how stiff they were. The results indicate that the original 0° PLA is the strongest material, whereas the altered 90° PLA-wood samples are the weakest.

3.1.3 Effect of Layer Thickness

In a review by Radhika et al [14] it was found that because the deposited material adhere properly to the substrate (causing weak inter layer bond), its tensile strength and fatigue life were worse than the substrate's properties. This could cause cracks to grow and eventually lead to structural damage.

According to Wu et al.'s research [43], samples constructed with a 300 μm layer thickness exhibited the highest strengths in every mechanical test, but samples with a 400 μm layer thickness showed a considerable loss in strength. Tensile strength was significantly influenced by layer thickness, although compressive and bending values were not significantly affected.

3.1.4 Effect of Material Used

For the majority of applications requiring chemical resistance, some qualities, like PEEK's excellent corrosion resistance, can be taken into consideration; however, each application demands a particular range of properties from the polymer in terms of yield strength and flexibility [24]. A number of processes, including corrosion, thermal stress, changing thermal cycle, and collision, can also cause damage to a component [8]. Therefore, the fatigue properties of polymer materials are significantly influenced by the type of material or alloy employed in AM procedures.

3.2 Methods to Determine Fatigue Property of AM Materials

3.2.1 Non-Destructive Tests (NDT)

A low-cost method based on the ultrasonic wave propagation velocities can be used to determine the fatigue property of AM materials [44]. Honarvar and Varvani-Farahani [45] looked at some non-destructive testing methods used in additive manufacturing and listed them as infrared thermographic testing (TT), X-ray computed tomography (CT), visual testing (VT), eddy current testing (ET), acoustic emission testing (AT), and ultrasonic testing (UT). Among these NDT methods, CT and UT showed the best results. One of the best ways to check industrial parts is through ultrasonic testing. Jung et al. [46] looked at how well 3D-printed CFRP resists fatigue using ultrasonic fatigue tests. Even though 3D printed items made with carbon fiber-reinforced plastic have many good qualities, their real-world use is still limited because more research is needed to understand how long they can last. In the study, three specimens were mixed in the bidirectional and unidirectional directions of 0° and 90° for an experiment. Numerical analysis verified the resonance at 20 kHz. The intended specimen was thoroughly examined using ultrasonic fatigue testing from low to high cycles, and longevity differences were verified through comparison. Based on the specimen's life analysis data, FEM was also utilised to predict the fatigue failure phenomenon.

3.2.2 Destructive Testing (DT)

Table 3. Some existing standards for destructive testing of fatigue of polymer materials according to American Society for Testing and Materials (ASTM) and international standard of organization (ISO)

TESTING STANDARD	APPLICATION	REFERENCE
ASTM E606	Strain-controlled fatigue testing	[47]
ASTM D3479	Tension–tension fatigue of polymer matrix composites	[48]
ISO 13003	Fatigue properties of fiber-reinforced plastics	[49]
ASTM D7774	Fatigue of plastics (Flexural)	[50]
ISO 15850	Tension–tension fatigue crack propagation	[51]
ASTM D7791	Uniaxial fatigue of plastics (tension or compression)	[52]
ASTM E739	Statistical analysis of linearized stress and strain life (S–N & ε–N) fatigue data	[53]
ASTM D6115	Propagation of cracks in fiber-reinforced polymer composites under load	[54]
ASTM D4482	Tensile fatigue of compounds made with rubber	[55]
ASTM D638	Tensile properties of plastics	[56]

Testing plastics for mechanical fatigue usually follows standards for samples made by injection molding, like ASTM D7791 or ISO 13003. For example, ASTM E606 works only with materials that are the same throughout (Homogenous), but FFF prints are naturally made up of different materials (Heterogenous). In notched fatigue tests, as described in ASTM D671 [57], cracks usually begin at the tip or notch, but this might not happen in 3D printed parts because they have many places where stress can build up. [58]. Additionally, ASTM D4482 indicates that the material being tested does not possess any initial cracks, which is an incorrect assumption for 3D printed parts where void gaps are present within the component [59]. These standards do not account for the total size effects, raster layups, and the build direction anisotropy inherent to 3D-printed parts, which often yields scattered, unrepeatable data due to the size effects of the micro-structure. Therefore, these test results are not often used with confidence.

4.0 Conclusion

All the literature reviewed reveals the increasing rate of industrial adoption of 3D printing and AM processes for functional, end-use components, therefore, Improving the fatigue life of these materials becomes a topic of study as it is a rapidly growing industry. Therefore, to enhance the mechanical integrity of 3D-printed components, a comprehensive design approach is needed. To enhance the fatigue characteristics of 3D printed polymer materials, the following areas have been discovered and should be improved on:

- Tailoring process parameters to the component's functional requirements enables the optimization of strength-to-weight ratios alongside other critical performance characteristics.
- This anisotropy must be kept in mind by designers of components that will be manufactured using additive manufacturing, and they must make sure that the orientations are conveyed to the simulation and printing stages.
- The fatigue behavior of additively manufactured polymers is a complex phenomenon governed by material chemistry, process parameters, and internal architecture.
- Establishing standardized fatigue testing protocols and advanced micro-mechanical predictive models will be essential to ensuring long-term reliability in dynamic engineering environments.
- Comparisons demonstrate that ultimate tensile strength (UTS) values exhibit sensitivity to higher layer thicknesses.

The fatigue life of additive manufactured polymer parts is highly sensitive to process parameters, hence, to ensure the reliability of AM components under cyclic loads, future engineers must move beyond "static strength" mindsets and consider the anisotropic nature of 3D-printed materials, taking major process parameters into consideration.

References

[1] L. Trávníček, F. Arbeiter, P. Dlhý, M. Spoerk, L. Náhlík, and P. Hutař, "Fatigue crack propagation in a component produced by additive manufacturing of polymer materials," *Procedia Structural Integrity*, vol. 42, pp. 141–147, 2022, doi: 10.1016/j.prostr.2022.12.018.

[2] M. Salmi, "Additive manufacturing processes in medical applications," *Materials*, vol. 14, no. 1, p. 191, 2021, doi: 10.3390/ma14010191.

[3] W. E. Frazier, "Metal additive manufacturing: A review," *Journal of Materials Engineering and Performance*, vol. 23, no. 6, pp. 1917–1928, 2014, doi: 10.1007/s11665-014-0958-z.

[4] O. Gülcan, K. Günaydın, and A. Tamer, "The state of the art of material jetting—A critical review," *Polymers*, vol. 13, no. 16, p. 2829, 2021, doi: 10.3390/polym13162829.

[5] M. Frascio, M. Avalle, and M. Monti, "Fatigue strength of plastics components made in additive manufacturing: First experimental results," *Procedia Structural Integrity*, vol. 12, pp. 32–43, 2018, doi: 10.1016/j.prostr.2018.11.109.

[6] V. Shanmugam et al., "Fatigue behaviour of FDM-3D printed polymers, polymeric composites and architected cellular materials," *International Journal of Fatigue*, vol. 143, p. 106007, 2021, doi: 10.1016/j.ijfatigue.2020.106007.

[7] S. Rouf, A. Raina, M. I. U. Haq, N. Naveed, S. Jeganmohan, and A. F. Kichloo, "3D printed parts and mechanical properties: Influencing parameters, sustainability aspects, global market scenario, challenges and applications," *Advanced Industrial and Engineering Polymer Research*, vol. 5, no. 3, pp. 143–158, 2022, doi: 10.1016/j.aiepr.2022.02.001.

[8] G. Piscopo and L. Iuliano, "Current research and industrial application of laser powder directed energy deposition," *The International Journal of Advanced Manufacturing Technology*, vol. 119, no. 11, pp. 6893–6917, 2022, doi: 10.1007/s00170-021-08596-w.

[9] S. S. Alghamdi, S. John, N. R. Choudhury, and N. K. Dutta, "Additive manufacturing of polymer materials: Progress, promise and challenges," *Polymers*, vol. 13, no. 5, p. 753, 2021, doi: 10.3390/polym13050753.

[10] S. C. Ligon, R. Liska, J. Stampfl, M. Gurr, and R. Mülhaupt, "Polymers for 3D printing and customized additive manufacturing," *Chemical Reviews*, vol. 117, no. 15, pp. 10212–10290, 2017, doi: 10.1021/acs.chemrev.7b00074.

[11] *Additive manufacturing — General principles — Fundamentals and vocabulary*, ISO/ASTM Standard 52900:2021, 2021. [Online]. Available: https://www.iso.org/standard/74514.html.

[12] L. J. Tan, W. Zhu, and K. Zhou, "Recent progress on polymer materials for additive manufacturing," *Advanced Functional Materials*, vol. 30, no. 43, p. 2003062, 2020, doi: 10.1002/adfm.202003062.

[13] H. A. Colorado, E. I. Gutierrez-Velasquez, L. D. Gil, and I. L. de Camargo, "Exploring the advantages and applications of nanocomposites produced via vat photopolymerization in additive manufacturing: A review," *Advanced Composites and Hybrid Materials*, vol. 7, no. 1, p. 1, 2024, doi: 10.1007/s42114-023-00808-z.

[14] C. Radhika, R. Shanmugam, M. Ramoni, and B. K. Gnanavel, "A review on additive manufacturing for aerospace application," *Materials Research Express*, vol. 11, no. 2, p. 022001, 2024, doi: 10.1088/2053-1591/ad21ad.

[15] Y. Chen, S. J. Clark, D. M. Collins, and L. Chen, "Melt pool morphology in directed energy deposition additive manufacturing process," *IOP Conference Series: Materials Science and Engineering*, vol. 861, no. 1, p. 012012, 2020, doi: 10.1088/1757-899X/861/1/012012.

[16] A. Elkaseer, K. J. Chen, J. C. Janhsen, O. Refle, V. Hagenmeyer, and S. G. Scholz, "Material jetting for advanced applications: A state-of-the-art review, gaps and future directions," *Additive Manufacturing*, vol. 60, p. 103270, 2022, doi: 10.1016/j.addma.2022.103270.

[17] H. Miyanaji, K. M. Rahman, M. Da, and C. B. Williams, "Effect of fine powder particles on quality of binder jetting parts," *Additive Manufacturing*, vol. 36, p. 101587, 2020, doi: 10.1016/j.addma.2020.101587.

[18] M. Ziaee and N. B. Crane, "Binder jetting: A review of process, materials, and methods," *Additive Manufacturing*, vol. 28, pp. 781–801, 2019, doi: 10.1016/j.addma.2019.05.031.

[19] M. Haddad, K. B. Nixon, and S. Wolff, "Sheet lamination," in *Springer Handbook of Additive Manufacturing*, E. Pei, M. Monzón, and A. Bernard, Eds. Cham, Switzerland: Springer, 2023, pp. 415–431, doi: 10.1007/978-3-031-20752-5_25.

[20] S. A. R. Naga and T. A. El-Sayed, "Fatigue failure in polymeric materials: Insights from experimental testing," *Journal of Failure Analysis and Prevention*, vol. 24, no. 2, pp. 922–935, 2024, doi: 10.1007/s11668-024-01874-1.

[21] S. E. Zeltmann, N. Gupta, N. G. Tsoutsos, M. Maniatakos, and R. Karri, "Manufacturing and security challenges in 3D printing," *JOM*, vol. 68, no. 7, pp. 1872–1881, 2016, doi: 10.1007/s11837-016-1937-7.

[22] G. D. Goh, Y. L. Yap, H. K. J. Tan, S. L. Sing, G. L. Goh, and W. Y. Yeong, "Process–structure–properties in polymer additive manufacturing via material extrusion: A review," *Critical Reviews in Solid State and Materials Sciences*, vol. 45, no. 2, pp. 113–133, 2019, doi: 10.1080/10408436.2018.1549977.

[23] A. Y. Kumar, Y. Bai, A. Eklund, and C. B. Williams, "The effects of Hot Isostatic Pressing on parts fabricated by binder jetting additive manufacturing," *Additive Manufacturing*, vol. 24, pp. 115–124, 2018, doi: 10.1016/j.addma.2018.09.021.

[24] J. M. Jafferson and D. Chatterjee, "A review on polymeric materials in additive manufacturing," *Materials Today: Proceedings*, vol. 46, pp. 1349–1365, 2021, doi: 10.1016/j.matpr.2021.02.485.

[25] A. Andrzejewska, Ł. Pejkowski, and T. Topoliński, "Tensile and fatigue behavior of additive manufactured polylactide," *3D Printing and Additive Manufacturing*, vol. 6, no. 5, pp. 272–280, 2019, doi: 10.1089/3dp.2017.0154.

[26] H. Alhashmi and S. Kumar, "Fatigue behaviour of PEEK fabricated by material extrusion additive manufacturing," *International Journal of Fatigue*, vol. 203, p. 109262, 2026, doi: 10.1016/j.ijfatigue.2025.109262.

[27] A. Marnot, K. Koube, S. Jang, N. Thadhani, J. Kacher, and B. Brettmann, "Material extrusion additive manufacturing of high particle loaded suspensions: A review of materials, processes and challenges," *Virtual and Physical Prototyping*, vol. 18, no. 1, p. e2279149, 2023, doi: 10.1080/17452759.2023.2279149.

[28] D. Wang et al., "Recent advances on additive manufacturing of heterogeneous/gradient metallic materials via laser powder bed fusion," *International Journal of Extreme Manufacturing*, vol. 7, no. 6, p. 062007, 2025, doi: 10.1088/2631-7990/adf69e.

[29] L. Liu et al., "Additive manufacturing of multi-materials with interfacial component gradient by in-situ powder mixing and laser powder bed fusion," *Journal of Alloys and Compounds*, vol. 978, p. 173508, 2024, doi: 10.1016/j.jallcom.2024.173508.

[30] B. O. Omiyale and P. K. Farayibi, "Additive manufacturing in the oil and gas industries: A review," *Analecta Technica Szegedinensia*, vol. 14, no. 1, pp. 9–18, 2020, doi: 10.14232/analecta.2020.1.9-18.

[31] W. Tang et al., "Materials and underlying principles in vat photopolymerization-based additive manufacturing of electronic ceramics," *Progress in Materials Science*, vol. 154, p. 101498, 2025, doi: 10.1016/j.pmatsci.2025.101498.

[32] D.-G. Ahn, "Directed energy deposition (DED) process: State of the art," *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 8, no. 2, pp. 703–742, 2021, doi: 10.1007/s40684-020-00302-7.

[33] T. Özel, H. Shokri, and R. Loizeau, "A review on wire-fed directed energy deposition-based metal additive manufacturing," *Journal of Manufacturing and Materials Processing*, vol. 7, no. 1, p. 45, 2023, doi: 10.3390/jmmp7010045.

[34] N. Gilani, A. Foerster, and N. T. Aboulkhair, "Material jetting," in *Springer Handbook of Additive Manufacturing*, E. Pei, M. Monzón, and A. Bernard, Eds. Cham, Switzerland: Springer, 2023, pp. 391–406, doi: 10.1007/978-3-031-20752-5_23.

[35] X. Chen et al., "The application and challenge of binder jet 3D printing technology in pharmaceutical manufacturing," *Pharmaceutics*, vol. 14, no. 12, p. 2589, 2022, doi: 10.3390/pharmaceutics14122589.

[36] X. Fang, Y. Zu, Q. Ma, and J. Hu, "State of the art of metal powder bonded binder jetting printing technology," *Discover Materials*, vol. 3, p. 15, 2023, doi: 10.1007/s43939-023-00050-w.

[37] A. Pilipović, "Sheet lamination," in *Polymers for 3D Printing: Methods, Properties, and Characteristics*, J. Izdebska-Podsiadły, Ed. Oxford, UK: William Andrew Publishing, 2022, pp. 127–136, doi: 10.1016/B978-0-12-818311-3.00008-2.

[38] T. Letcher and M. Waytashek, "Material Property Testing of 3D-Printed Specimen in PLA on an Entry-Level 3D Printer," in *Proceedings of the ASME 2014 International Mechanical Engineering Congress and Exposition*, Vol. 2A: Advanced Manufacturing, Montreal, Quebec, Canada, Nov. 14–20, 2014, Paper No. V02AT02A014, doi: 10.1115/IMECE2014-39379.

[39] H. Gonabadi, Y. Chen, A. Yadav, and A. S. Bull, "Investigation of the effect of raster angle, build orientation, and infill density on the elastic response of 3D printed parts using finite element microstructural modeling and homogenization techniques," *The International Journal of Advanced Manufacturing Technology*, vol. 118, no. 5-6, pp. 1485–1510, 2022, doi: 10.1007/s00170-021-07940-4.

[40] A. Farzadi, M. Solati-Hashjin, M. Asadi-Eydivand, and N. A. Abu Osman, "Effect of layer thickness and printing orientation on mechanical properties and dimensional accuracy of 3D printed porous samples for bone tissue engineering," *PLoS ONE*, vol. 9, no. 9, p. e108252, 2014, doi: 10.1371/journal.pone.0108252.

[41] M. Azadi, A. Dadashi, S. Dezianian, M. Kianifar, S. Torkaman, and M. Chiyani, "High-cycle bending fatigue properties of additive-manufactured ABS and PLA polymers fabricated by fused deposition modeling 3D printing," *Forces in Mechanics*, vol. 3, p. 100016, 2021, doi: 10.1016/j.finmec.2021.100016.

[42] M. R. Khosravani, S. Rezaei, H. Ruan, and T. Reinicke, "Fracture behavior of anisotropic 3D-printed parts: Experiments and numerical simulations," *Journal of Materials Research and Technology*, vol. 19, pp. 1260–1270, 2022, doi: 10.1016/j.jmrt.2022.05.068.

[43] W. Wu, P. Geng, G. Li, D. Zhao, H. Zhang, and J. Zhao, "Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-Printed PEEK and a Comparative Mechanical Study between PEEK and ABS," *Materials*, vol. 8, no. 9, pp. 5834–5846, 2015, doi: 10.3390/ma8095271.

[44] H. R. Javidrad and S. Salemi, "Determination of elastic constants of additive manufactured Inconel 625 specimens using an ultrasonic technique," *The International Journal of Advanced Manufacturing Technology*, vol. 107, no. 11, pp. 4597–4607, 2020, doi: 10.1007/s00170-020-05321-x.

[45] F. Honarvar and A. Varvani-Farahani, "A review of ultrasonic testing applications in additive manufacturing: Defect evaluation, material characterization, and process control," *Ultrasonics*, vol. 108, p. 106227, 2020, doi: 10.1016/j.ultras.2020.106227.

[46] C. Jung, Y. Kang, H. Song, M. G. Lee, and Y. P. Jeon, "Ultrasonic fatigue analysis of 3D-printed carbon fiber reinforced plastic," *Heliyon*, vol. 8, no. 11, p. e11671, 2022, doi: 10.1016/j.heliyon.2022.e11671.

[47] *Standard Practice for Strain-Controlled Fatigue Testing*, ASTM E606, ASTM International, West Conshohocken, PA, 1998.

[48] *Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials*, ASTM D3479, ASTM International, West Conshohocken, PA, 2012.

[49] *Fiber-reinforced plastics—Determination of fatigue properties under cyclic loading conditions*, ISO Standard 13003:2003, International Organization for Standardization, Geneva, Switzerland, 2003.

[50] *Standard Test Method for Flexural Fatigue Properties of Plastics*, ASTM D7774-12, ASTM International, West Conshohocken, PA, 2012.

[51] *Plastics—Determination of tension-tension fatigue crack propagation—Linear elastic fracture mechanics (LEFM) approach*, ISO Standard 15850:2014, International Organization for Standardization, Geneva, Switzerland, 2014.

[52] *Standard Test Method for Uniaxial Fatigue Properties of Plastics*, ASTM D7791-12, ASTM International, West Conshohocken, PA, 2017.

[53] *Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) fatigue data*, ASTM E739-91, ASTM International, West Conshohocken, PA, 2015.

[54] *Standard Test Method for Mode I Fatigue Delamination Growth Onset of Unidirectional Fiber-Reinforced Polymer Matrix Composites*, ASTM D6115-97, ASTM International, West Conshohocken, PA, 2011.

[55] *Standard Test Method for Rubber Property—Extension Cycling Fatigue*, ASTM D4482-11, ASTM International, West Conshohocken, PA, 2017.

[56] *Standard Test Method for Tensile Properties of Plastics*, ASTM D638, ASTM International, West Conshohocken, PA, 2014.

[57] *Standard Test Method for Flexural Fatigue of Plastics by Constant-Amplitude-of-Force (Withdrawn 2002)*, ASTM D671-93, ASTM International, West Conshohocken, PA, 1993.

[58] A. M. Forster, "Materials testing standards for additive manufacturing of polymer materials: State of the art and standards applicability," National Institute of Standards and Technology, Gaithersburg, MD, Report No. NIST.IR.8059, 2015, doi: 10.6028/nist.ir.8059.
[59] H. Bakhtiari, M. Aamir, and T. Tolouei-Rad, "Effect of 3D printing parameters on the fatigue properties of parts manufactured by fused filament fabrication: A review," *Applied Sciences*, vol. 13, no. 2, p. 904, 2023, doi: 10.3390/app13020904.

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