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Finite element analysis in fused deposition modeling research: A literature review

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ABSTRACT

Fused Deposition Modelling (FDM) is a popular rapid prototyping technique. Finite Element (FE) methods are generally applied in simulations of the FDM process. Mostly FE methods are used for initial analysis which are compared with experimental methods. The main objective of this paper is reviewing the existing literature related to finite element methods in FDM research and pointing out some limitations. For the literature review, the selected papers are divided into three domains: thermal analysis, geometrical analysis, and mechanical characterization. It is found that there is no FE model on surface finish and geometrical analysis. However, there are geometrical simulation models on surface finish and geometrical analysis. It is also found that there is no realistic FE model in the existing literature. Realistic FE models are very much required for increasing the prediction accuracy of the models. For this reason, researchers should more focus on the FE analysis of FDM fabricated parts.

1. Introduction

With the advancement of information technology, 3D printing methods are now extensively used in manufacturing firms to connect and increase productivity. 3D printing techniques are considered as the future of the manufacturing world [1,2]. These processes are also popularly known as Additive Manufacturing (AM) or Rapid Prototyping (RP) [3–5]. The capability of producing complex parts [6,7], minimum material loss, and no requirement of fixtures have made these processes cost-effective and faster than other processes. There are about 20 RP technologies available in the world. Due to simple operational steps, the FDM is one of the most widely used AM processes [8–16]. FDM is the second most prominent RP technology after stereolithography [17]. Moreover, FDM is capable of safe and neat fabrication of complex geometry in office-friendly surroundings.

Stratasys Inc., USA first introduced FDM in the early 1990 s [18,19]. Generally different thermoplastic materials [20–23] like poly-lactic acid (PLA), reinforced PLA [24], acrylonitrile butadiene styrene (ABS) [25–29], polycarbonate (PC), polyurethanes [31] and PCABS blend are used in FDM process. Recently, the researchers are exploring new materials like ceramics[32], PLA/biphasic calcium phosphate [33], polymer-bioactive glass composites [34], poly-caprolactone (PCL)-based composites [35], biomaterials [36], low melting point alloys [37] etc. for FDM. The researchers are also researching on sandwich structures of multiple polymers [38]. In FDM, generally, thermoplastic materials are melted using a liquefier. Afterward, the melted material is deposited layer by layer through a nozzle following the input CAD model in Standard Triangulation Language (STL) file format [32,35,36,39–42]. Melted material deposits on the heat bed through the nozzle movement in the X-Y direction. The melted material then cools and solidifies on the heat bed [43–45]. The heat bed temperature is maintained at a lower temperature to facilitate the solidification process [8,46]. Finally, post-processing is done for getting the near net shape. The steps of the FDM process is mentioned in Fig. 1 and the schematic diagram of FDM process is presented in Fig. 2.

Numerical simulation methods are of two kinds: mesh-free methods and mesh-based methods. The finite volume method (FVM) and Lattice Boltzmann method (LBM) are mesh free methods. The mesh-free methods are less popular compared to mesh-based methods. Mesh-free methods are mainly used for studying fluid dynamic characteristics of AMed parts [47]. On the other hand, mesh-based methods, such as, finite element method (FEM) reduces the problem to a finite number of unknown variables discretizing the domain. It has become an easier and essential tool for solving eigenvalue, initial value, and boundary value problems. This tool is simple because each finite element is a simpler geometry compared to the complex actual structure. Moreover, parametric optimization has made FEM more popular. For these reasons, FEM is heavily used to simulate AM processes to save time and resources

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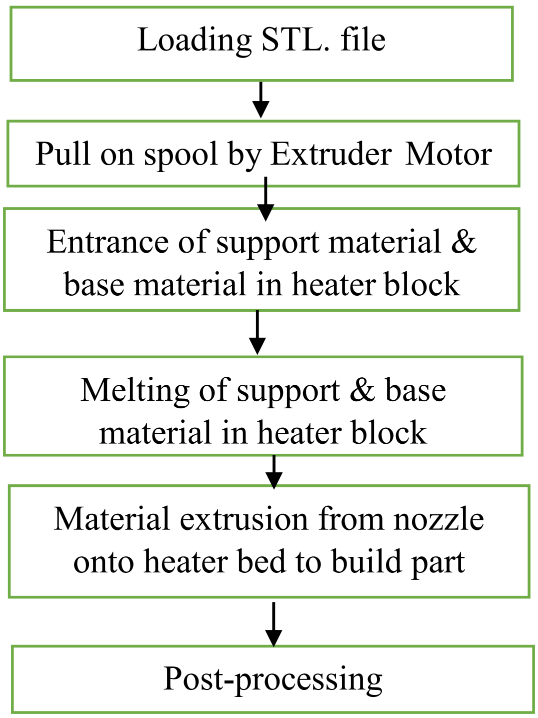

Fig 1. Steps of FDM.

by avoiding a large number of physical experiments [48–50].

The number of review articles on simulation techniques of AM processes is too little. Taufik et al. [42] have presented a review of the surface quality of FDM parts based on preprocessing and post-processing studies. Vyvahare et al [46] did a comprehensive analysis of FDM research studying 200 papers published from 1994 to 2019. They reported that only 6% of the published articles contain numerical simulation of the FDM process. As a subset of numerical simulations, papers on FE analysis of FDM parts are much less in percentage.

From an extensive literature survey, it is found that no review article exists on FE analyses in FDM research. Though there is no review article on FEA in FDM research, it is an important reesrach topic in manufacturing research for several reasons. FEA can decrease material costs and costs of experimental trials. Also, the existing FE models in FDM research is far from being realistic. Moreover, the existing FE models are not computationally efficient. It is important to identify the existing research gaps to move forward research in this topic to improve accuracy and efficiency of the FE models. If efficient and coupled thermo-mechanical and geometrical error analysis can be done, there will be a lot of cost-saving for the manufacturing industry. It will immensely help the manufacturing industry, doing accurate predictions of the part characteristics before manufacturing.

The main objectives of this paper are as follows:

- Review the literature which includes finite element analysis to simulate FDMed parts.
- Identifying research gaps of finite element modeling in FDM research.
- Providing future research directions analyzing the research gaps.

To summarize the manuscript, it is the first review paper on FE analysis in FDM research. From the detailed literature review, it is found that only a handful of works have been done on the FEA of FDMed parts. It is also found that there is no FE model for surface quality analysis. In addition to that, the FE models should be more realistic to get better results. Also, the computational efficiency highly depends on the

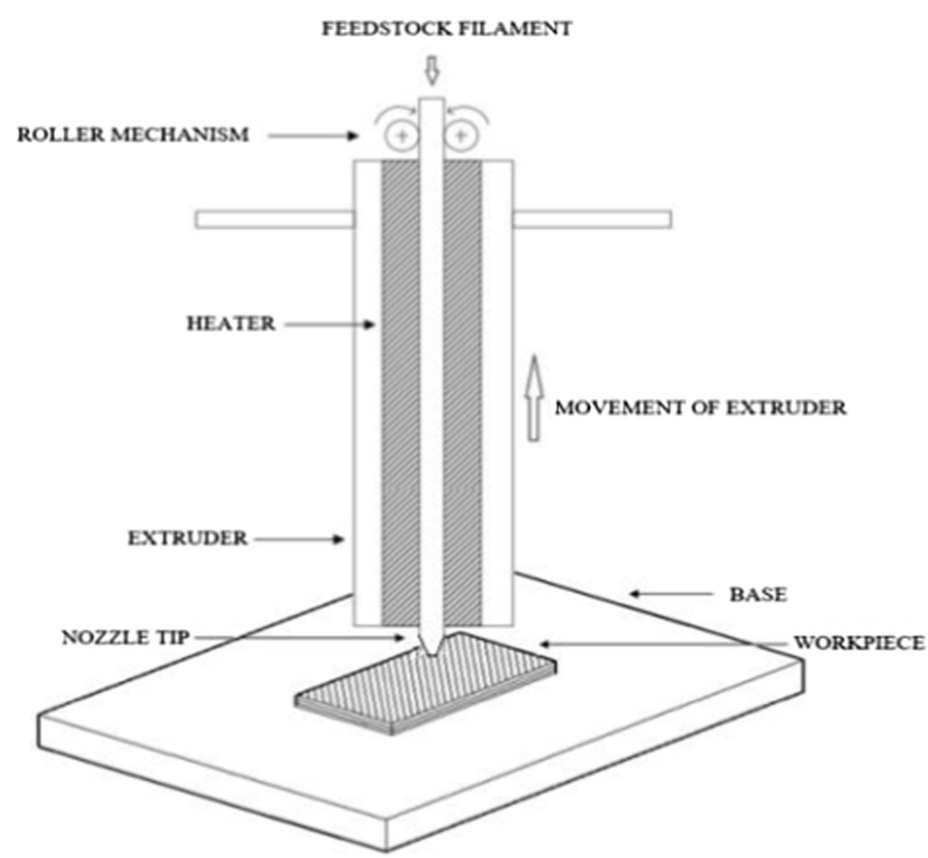

Fig 2. Schematic Diagram of the FDM process [46]

meshing technique. Cloud and parallel computing can be introduced to increase computational efficiency. For these reasons, the researchers should concentrate more on this research topic.

The structure of this article is as follows. The relevant literature is reviewed in **Section 2**. The research gaps and future research direction are presented in the following section, followed by a conclusion in **Section 4**.

2. Literature review

This section contains explanation of some keywords followed by relevant literature.

2.1. Some keywords with explanation

This sub-section presents the explanation of some important keywords.

Fused Deposition Modeling (FDM): Fused Deposition Modelling, popularly known as FDM, is based on the material extrusion process. In this manufacturing process, thermoplastic filament is melted in liquefier and extruded through the nozzle. The parts are manufactured from the extruded melted filament according to the input G-code. The FDM is generally used for rapid prototyping thermoplastic specimens. FDM is mainly popular for desktop 3D printing applications due to low operational and maintenance costs [51].

Finite Element Analysis (FEA): FEA is a popular mathematical technique for finding approximate solutions of partial differential equations. The solutions of the partial differential equations are mainly based on an expansion of the dependent variable(s) into a linear combination of polynomial trial functions defined over elements. FEA is useful because it breaks a large problem into a finite number of unknown variables. FEA is generally used for structural analysis, coupled thermo-mechanical analysis, thermal analysis, etc.

Rapid Prototyping (RP): Rapid Prototyping is based on additive layer manufacturing to quickly manufacture prototypes from CAD STL. file. RP is mainly used to quickly manufacture prototypes to test them before manufacturing the real part, to reduce cost. Nowadays, RP techniques have become advanced. RP techniques are now generally used in the automobile industry, aerospace industry, consumer products, etc [41]. For the extensive application of RP techniques in several sectors, RP techniques are considered the future of the manufacturing industry.

2.2. Relevant literature

Before writing the paper, relevant literature is searched in Google Scholar using keywords- 'finite element analysis', 'additive manufacturing', 'fused deposition modeling', 'numerical simulations of FDM', and 'rapid prototyping'. The papers reviewed in this review paper can be divided into three domains: thermal analysis, geometrical analysis, and mechanical characterization. The related papers in these three domains are reviewed in the following sub-sections.

2.2.1. Mechanical characterization through FE simulation

The effects of different process parameters on mechanical characteristics, for example, elongation, tensile stress, fracture toughness, etc. are dominant in FE analysis of the FDMed parts. Bellini & Güçeri [52] combined FE analysis and tensile test data to predict the stiffness of FDM built ABS parts.

There are some FE models for cellular FDM parts. Hussey et al. [53] analyzed an open-cell structure (self-interlocking assemblies) FDMed parts in ABAQUS to get an insight into the mechanical performance of these structures. Karamooz et al [54] performed finite element analysis on BCC-Z unit cell fabricated by the FDM process using commercially available software ABAQUS/STANDARD for both beam and solid model. They used second-order tetrahedral continuum element C3D10M for meshing. They applied the simulation of the cell under compression stress. It was found that the beam model was more computationally efficient than the solid model. However, for elastic modulus, both models showed almost similar results. Afterward, the simulation results were compared with parts fabricated with PLA. Fig. 3 shows the stress–strain curves for different mesh sizes of the proposed FE model and compares them with experimental analysis (see Fig. 4).

Ahn, Baek, Lee, & Ahn [55] analyzed the tensile failure behaviors of Stratasys' FDM. FDM fabricated parts have anisotropic characteristics for the process mechanism. Four specimens were analyzed in this study. The air gap of the specimens was kept constant. The specimens differed only in the raster angle. ABS was used as the material for the FDM process to make the specimens. Classical Lamination Theory and Tsai-Wu failure criterion were applied to predict the failure behaviors of FDM specimens using computer code. The failure load values were compared with predicted values from the software which showed good agreement between predicted and experimental values. However, the failure properties of the specimens with different air gaps were not mentioned in their work.

Garg & Bhattacharya [56] tried to present a realistic FE model which included three different layer thicknesses (0.254 mm, 0.178 mm, 0.330 mm), three different raster angles (0 degree, 0 degree/ 90 degrees, 90 degrees), and intra-layer and inter-layer bonded regions. This elasto-plastic behavior simulation of the FDM process was later experimentally validated. The FE analysis and experimental validation identified that the elongation, tensile strength, stress, and strain at yield first decreases and later increases with increasing layer thickness. The sample with 0.33 mm layer thickness showed higher tensile strength due to higher intra-layer bond areas and air voids. The samples which have a layer thickness of 0.178 mm show higher elongation and load-bearing capacity than samples with layer thickness of 0.33 mm and 0.254 mm. They also confirmed through FE analysis and fractographic analyses that the failure in 90 degree raster occurs after the brittle fracture of 0 degree raster. In addition to that, the study reports that 0 degree raster fails due to pulling and rupture of fibers.

Some researchers used the orthotropic material model for the FEA of FDM parts. Martinez et al. [57] used an orthotropic material model to compare layered unidirectional composite FDM parts and layered fiber crossed composite FDM parts in ABAQUS. Domingo-Espin et al. [59] also used the orthotropic material model to analyze the effect of build orientation on the mechanical behavior of FDM parts. Farbman & McCoy, (2016) analyzed the effect of infill patterns on the mechanical behavior of FDM parts incorporating the infill patterns in CAD model that can be observed with naked eyes.

Webbe Kerekes, Lim, Joe, & Yun [61] identified the effects of layer thickness and infill percentage on modulus of toughness, ultimate strength, initial yield stress, Young's modulus, and elongation at break of FDM parts. A total of 30 samples in six groups were tested and compared with the Gurson-type porous model with a 3D continuum FE model for characterizing process-damage relationship with an inverse identification process. The FE model was analyzed with commercial software ABAQUS. The authors identified the optimum material properties with Chaotic Firefly Algorithm as it is an efficient global optimizer. They analyzed six combinations of the two process parameters: three infill percentage- solid, high, and low (Fig. 5) and two layer thickness values- 0.254 mm and 0.33 mm. The prediction error of the FE model was between 0 and 8 percent of the experimental results. The authors experimentally verified the results using three techniques- digital image correlation, X-ray micro-computed tomography, and in situ tensile testing using optical microscopy. However, the work has some limitations. The FE model is unable to predict non-uniform strains which were found experimentally. Multi-scale FE model should incorporate thermo-induced residual stress prediction, nonlinearity consideration for analyzing pre-selected structures and FDM print patterns for future research to make the model more realistic (see Fig. 6).

Some authors used isotropic material despite realistic anisotropic

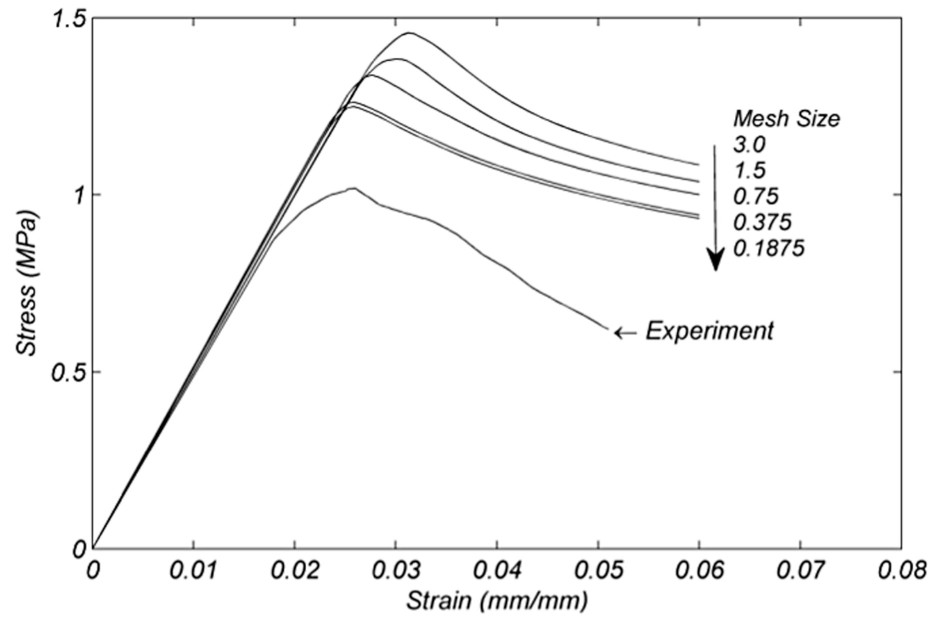

Fig 3. Stress–strain curve presented by Karamooz et al [54]

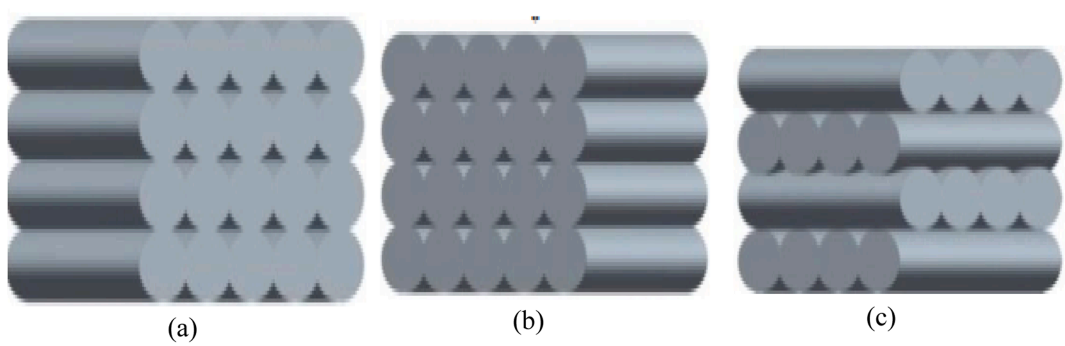

Fig 4. Three raster angles used by Garg & Bhattacharya [56] a) 0degree b) 90 degree c) 0 degree/ 90 degree.

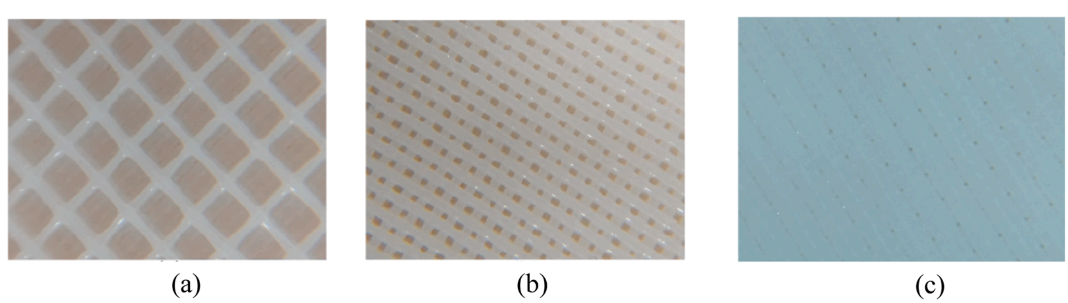

Fig 5. (a) Low (b) High and (c) Solid infill options used by Webbe Kerekes, Lim, Joe, & Yun [61]

material in their proposed FE models for simplicity. Umetani et al. [62] applied the Euler-Bernoulli assumption which reduced the complexity of their FE model. They used isotropic material assumption to detect critical stress inside FDM printed objects based on the bending moment equilibrium equation. Bhandari & Lopez-Anido [63] predicted linear elastic response of test coupons ULTEM 9095 fabricated part with an isotropic material model. They used the space frame lattice and shell FE model to optimize and make efficient design for 3-D printed parts. Guessasma, Belhabib, & Nouri [65] compared the isotropic material FE model for presenting pore connectivity and microstructure related heterogeneity. The model is then compared with the experimental method using X-ray tomography. Lanzillotti, Gardan, Makke, & Recho [66] identified the effect of thread deposition on fracture toughness of ABS specimens. They showed that the proposed optimized deposition increased maximum force in fracture up to 20 percent and fracture toughness of the stress intensity factor increased about 30 percent. On the contrary to these isotropic material models, Guessasma, Belhabib, Nouri, & Ben Hassana [65] modelled damage under compressive loading with a 2-D FE model for anisotropic FDMed parts.

Taylor, Mares, Rane, & Love [67] first ever used 3-D printing in aeroelastic modeling. They compared cantilever beam testing and three-point bend tests result with FE modeling for elastic scaling of an aero-

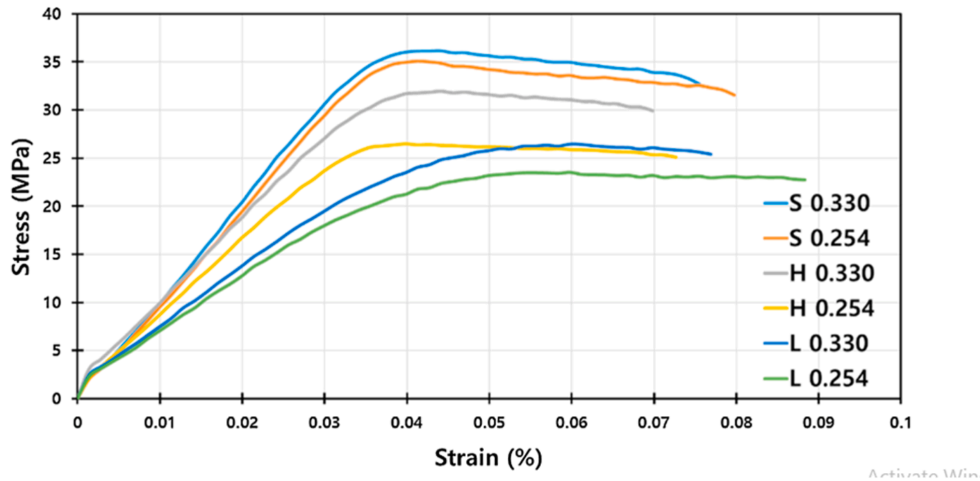

Fig 6. Comparison of the stress–strain curve of six samples [46]

elastic wind tunnel. The authors performed a linear static analysis using Altair OptiStruct. The models applied first-order CQUAD4 elements with PSHELL property cards. The authors analyzed several process parameters: material integrity, resulting in effective modulus, geometric sensitivity, and bead continuity to print orientation. Two printing orientations were used for analysis: 0 degree stiffened plates for material modulus 181 ksi and 45 degree stiffened plates for material modulus 161 ksi. The authors found that 45 degree stiffened plates showed significant differences and 0 degree stiffened plates showed good agreement between the FE model and experimental methods. As a future work, the authors suggested other process parameters such as bead overlap can be added to the model to predict structural stiffness.

2.2.2. Geometric error and surface roughness simulation models

Surface roughness improvement of RP fabricated parts are of major concerns found in different literature [16,17]. Mainly these works are related to the effects of different parameters like layer thickness, material flow pressure, generation time, build orientation, etc. Even though FDM is the most widely used AM process, it has been found that the surface quality of FDM has been least explored in literature [8].

In Fig. 7 we can see the schematic representation of deposition and building direction and building angle during an FDM process. Due to this type of layered manufacturing process, the edge quality and surface quality decrease due to several reasons: staircase effect, offset of tool path, radius, removal of support, slicing effect, and swelling [42]. Different numerical and analytic models were proposed for minimizing different geometrical errors like stack up of layer to layer flatness errors, differential shrinkage warpage, deposition head vibration, machine drive inaccuracies, layer discretization [69].

No FE model on surface quality and geometric error analysis is found in the existing literature. Several geometrical models have been proposed in different literature for edge quality and surface quality evaluation. Armillotta & Cavallaro [70] introduced three characteristic angles rather than only one inclination angle. They also found out some causes of edge and surface errors. Armillotta [69] further carried on the research and proposed a graphical simulation method for FDM parts considering the three characteristic angles (inclination angle α, included angle β and incidence angle γ) and the layer thickness for simulating position and form error (Fig. 8). Position error is the average distance of the points from the nominal profile whereas form error is the root mean square difference of those distances. It was found from experimental evidence that the simulated edge profiles were correctly predicted through simulation. However, the research was only based on the errors mentioned by Armillotta & Cavallaro [70]. More types and kinds of error should be included for further research and it is utterly important to initiate research on FE models of surface finish and geometrical error analysis of samples manufactured in the FDM process.

It is found that optimizing the process parameters can improve the surface finish of the parts manufactured in FDM process. However, more improvement is required for industrial applications [71]. For these reasons, some researchers are using strengthening mechanisms to improve tensile strength and surface finish of manufactured parts. Unlike other AM processes, as FDM is mainly applicable for thermoplastics, CNC machining[42,72], laser polishing, and fiber reinforcement are mostly used techniques to improve surface finish and tensile strength of the parts [71,73]. Carneiro et al. [74] showed that filament of glass fiber reinforced polypropylene composites increases 30% elastic modulus and 40% strength compared to pure polymer. Carbon fiber reinforcement of the polymers also showed improved electrical, mechanical, and thermal

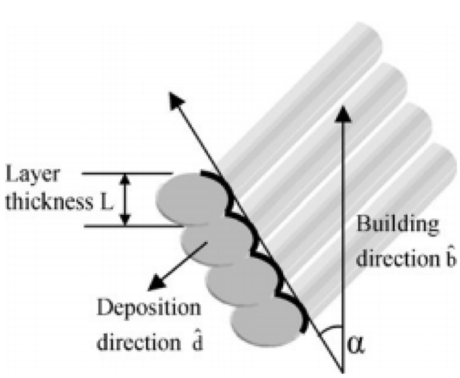

Fig 7. Schematic diagram of material deposition and building direction [68]

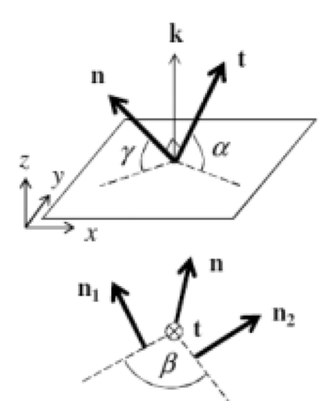

Fig 8. Three characteristic angles introduced by Armillotta [69]

properties. Chen et al. [73] reported that FDM parts fabricated with Cu/PLA composite and laser polishing reduced surface roughness more than 91% as laser polishing eliminated interlayer, intra-layer, and interfacial voids.

2.2.3. Simulation of thermal models

Advancement of numerical methods and computational capacity have facilitated accurate prediction of thermal history in AM processes [75–80]. In the FDM process, the temperature is unevenly distributed while manufacturing the part. Due to latent heat for phase transition, the manufactured parts are susceptible to deformation and other thermal defects. Despite the high importance of research on this topic, the current research is insufficient. It is utterly necessary to select optimal process parameters and correct materials to reduce the temperature gradient to alleviate the thermal stress formation [81–83]. In the FDM process, convection and conduction are the dominant modes of heat transfer [84]. Eqs. (1)–(4) the governing equations for FE analysis.

$$\text{Conduction}: \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q} = \rho Cp\frac{\partial T}{\partial t}(\text{Fourier'sequation}) \quad (1)$$

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q} = \rho\frac{\partial H}{\partial t}(\text{Forenthalpychange}) \quad (2)$$

where, $dH = CpdT$

$$\text{Convection}: \dot{Q} = h(T - T_0) \quad (3)$$

$$\text{Radiation}: \dot{Q} = \sigma\varepsilon\left(T^4 - T_0^4\right) \quad (4)$$

where, *Cp* is the molar specific heat at constant pressure, h is convection coefficient, $\sigma \text{isStefan} - \text{Boltzmannconstant}, \text{and}\varepsilon \text{istheemissivity}$.

Some FE simulation models are related to residual stresses in the FDM process. Zhang & Chou [23] studied thermal and mechanical processes with part distortions and residual stress distributions by element activation in FE Analysis to simulate the FDM deposition process in ANSYS. It is observed that at the tool path turning points, there are greater thermal gradients and stress accumulation marks. It is also found that long and alternate raster pattern leaves less residual stress than short-raster patterns. They also observed that the long raster parts deform in the length-side and short-raster parts in the width side. However, the model lacks realistic boundary conditions and experimental validation. Some thermal models are based on the birth and death of elements. Ji & Zhou [81] presented a 3-D transient thermal nonlinear FE model for FDM using ANSYS parametric design language (APDL) considering latent heat enthalpy. They used ABS as the material for their model. The results showed that temperature field distribution is an ellipse. In addition to that, they found that the temperature gradient was the greatest near the edges of the manufactured part.

Zhou, Nyberg, Xiong, & Liu [83] presented FDM process simulation and temperature distribution for ABS material focusing on heat conductivity. They analyzed a 3-D space discrete FE model with Chernoff energy for predicting a process time discretization for solving differential equations. The model is based on two assumptions: semi-infinite filament length, and uniform temperature distribution across the cross-section of the filament. The cross-section of the filament and support were meshed using ANSYS SHELL281 element for better accuracy and SOLID90 with 20 nodes was applied after extruding the previously meshed section. The support was kept at room temperature for the simulation.

The aforementioned thermal analyses either completely lack experimental validation or validated through indirect results of thermal behavior. Therefore, X. Zhou, Hsieh, & Sun [85] proposed an experimental method to quantify filament temperature under deposition using the IR sensor. They simulated the FE model in ANSYS 17.2 to predict thermal stress distribution and temperature of the process. They are the first to use polymer bonding theory in numerical simulation of FDMed parts. They also identified the effects of platform temperature, nozzle temperature, layer thickness, and extrusion speed on diffusion time and maximum vertical distortion. Both the experimental and the FE analysis results predicted that PLA shows the highest diffusion time in high nozzle temperature, high layer thickness, low printing speed, and high platform temperature. In addition to that, the proposed FE model found that reducing extrusion temperature, decreasing layer thickness, and slowing printing speed reduce vertical distortion and residual thermal stress.

3. Research gaps

Like other AM methods, FE analysis of FDM is very difficult [81] due to high computational effort for the transient nature of the process. However, it is very important to simulate numerical models for saving money for conducting repetitive experiments [47]. From an extensive literature search, it can be concluded that the number of papers on the FE analysis of FDM is still very low compared to other AM techniques. Moreover, from the summary of the reviewed literature presented in Table 1, most of the literature is related to thermoplastic materials, mostly ABS. The researchers should initiate their research on this topic using other materials like different low melting point metal alloys, different metals, and difficult to manufacture materials.

The FE analyses presented in the current literature of the FDM process are mostly mechanical characterization. Some thermal models were also proposed. However, the proposed FE models are far from capturing the reality of the world. Many factors were not considered in the FE models to keep the computational efforts less. Most of the models do not consider environmental factors, such as room temperature, humidity, etc. In addition to that, despite the increased need for research on the effect of process and environmental parameters on surface roughness improvement and geometrical error reduction, the relevant research applying the FE model is non-existent in current literature.

The researchers should concentrate on the research on combined thermal, mechanical, and geometrical error analysis to create more realistic FE models. Wang et al. [90] established warp deformation modeling. Yang et al. [87] did a non-linear thermal-structural coupled analysis to study four different scanning filling patterns: honeycomb, grid, rectilinear, and wiggle. They found that the honeycomb structure provides the smallest deformation and most uniform stress distribution. Alafaghani et al.[88] considered porosity in their thermo-mechanical analysis of FDM parts. They identified that fracture resistance increases with increasing printing temperature. Cattenone, Morganti, Alaimo, & Auricchio [89] simulated a bridge model and a spring model in ABAQUS and performed a sensitivity analysis to find perfect time step size and mesh size. They applied Dirichlet boundary conditions with thermo-elastoplastic constitutive law for their simulation to find out mechanical behaviors for the cooling of FDMed parts. Their prediction from simulation aligns with experimental validation. Experimental validation with the ABS fabricated parts showed that the spring model has appreciable warpage at the corners and the bridge model shows simulation predicted Z displacement and anomalous effects. However, they did not consider adhesion between the layers. More research should be conducted in this domain.

From Table 1 it is clear that the most of the FE analysis of FDM research was conducted using commercial software ABAQUS and ANSYS. These software packages are not much computationally efficient for modeling transient processes like FDM. Therefore, it is very much needed to build software that will be dedicated to AM research which will be able to do the analyses more efficiently. Cloud-based parallel computing and effective knowledge management can be better alternatives [91–93].

Table 1
Literature summary.

Author (Year)	Material	Dimension	FE analysis	Experimental Validation	Parameters Analyzed	Output
Karamooz et al. (2014) [54]	PLA	3	ABAQUS	Compression stress test	N/A	Compression stress
Ahn et al. (2003) [86]	ABS	3	Computer code based on Tsai-Wu failure criterion and Classical Lamination Theory	N/A	Raster angle	Failure properties of FDM parts
Garg & Bhattacharya (2017) [56]	ABS	3	ABAQUS	Fractographic analyses using a 3D optical profiler, optical microscope, and scanning electron microscopy (SEM)	Layer thickness and Raster angle	Elongation, tensile strength, stress and strain at yield
Domingo-Espin et al. (2015) [59]	PC	3	ANSYS	N/A	Build orientation	Mechanical behavior
Webbe et al. (2019) [61]	Optimized material property using Chaotic Firefly Algorithm	3	ABAQUS	Digital image correlation, X-ray micro-computed tomography, and optical microscopy in situ tensile testing	Layer thickness and infill percentage	Ultimate strength, Young's modulus, modulus of toughness, initial yield stress, and elongation at break
Bhandari & Lopez-Anido (2018) [63]	Polyetherimide	3	ABAQUS	Quasi-static mechanical experiments	N/A	Shear modulus, elastic modulus, and Poisson's ratio
Guessasma et al. (2015) [64]	ABS	2	Comsol	X-ray micro-tomography	Porosity and Build orientation	Damage under compressive load
Guessasma, Belhabib, & Nouri (2016) [65]	ABS		ANSYS multi-physics	X-ray microtomography	Porosity	Pore connectivity and microstructure related heterogeneity
Bellini & Güçeri (2003) [52]	ABS	3	ANSYS	Three-point bending test, and tensile test	Tensile test data	Stiffness of FDM built part.
Yang et al. (2018) [87]	PLA	3	ABAQUS	N/A	Scanning filling patterns	Deformation, stress distribution
Alafaghani et al. (2017) [88]	PLA	3	ABAQUS	SEM imaging, Universal testing machine	Building direction, infill percentage, infill pattern	Fracture resistance
Umetani et al. (2013)[62]	PLA	3	N/A	N/A	Second-order linear FEM stress analysis	Bending moment
Martinez et al. (2013) [57]	ABS (orthotropic material model)	3	ABAQUS	N/A	N/A	Comparison of two composite models
Taylor, Mares, Rane, & Love (2019) [67]	Orthotropic material	3	Altair OptiStruct	Cantilever beam testing and three-point bend test	Material integrity, resulting effective modulus, geometric sensitivity, and bead continuity to print orientation	Stiffness
Armillotta (2019) [69]	N/A	3	Graphical simulation	N/A	Inclination angle α, included angle β, and incidence angle γ	position and form error
Zhang & Chou (2006) [84]	ABS	3	ANSYS	N/A	Raster patterns	Part distortions and residual stress distributions
Ji & Zhou (2010) [81]	ABS	3	ANSYS APDL	N/A	N/A	Temperature field distribution
Zhou, Nyberg, Xiong, & Liu (2016) [83]	ABS	3	ANSYS using Chernoff energy	N/A	N/A	Temperature field distribution
X. Zhou, Hsieh, & Sun (2017) [85]	PLA	3	ANSYS	IR sensor data	Platform temperature, nozzle temperature, extrusion speed, and layer thickness	Filament temperature under deposition, diffusion time, and maximum vertical distortion
Armillotta & Cavallaro (2017) [70]	N/A	3	Graphical simulation	N/A	Inclination angle	Edge and surface error
Farbman & McCoy (2016) [60]	ABS, PLA	3	Not Mentioned	Monotonic tensile tests, fracture of test specimens	Infill patterns	Mechanical behavior
Cattenone, Morganti, Alaimo, & Auricchio (2019) [89]	ABS	3	Simulating a bridge model and a spring model in ABAQUS	Z-axis displacement	Time step and meshing strategy	mechanical behaviors for cooling of FDM parts
Cattenone et al. (2019) [89]	ABS	3	ABAQUS	Z-axis displacement	Mesh size, material model, time step size, temperature	Thermal stress, Von-Mises stress
		3	ABAQUS			

(continued on next page)

Table 1 (*continued*)

Author (Year)	Material	Dimension	FE analysis	Experimental Validation	Parameters Analyzed	Output
Hussey et al. (2020) [50]	PCL (Solid homogenous material model)			Cyclic compression and Tensile test, SEM characterization	Fatigue behavior, Tensile and Compressive strength,	Mechanical properties characterization
Lanzillotti et al. (2019) [66]	ABS	3	SolidWorks	Tensile test	Optimized thread deposition	Fracture toughness

4. Concluding remarks

In this article, the FE models in FDM research are presented. The article also identifies certain gaps in the existing literature. From the literature review and the identified research gaps, the following remarks can be concluded:

- The computational efficiency of FE modeling depends highly on proper meshing.
- The failure mechanism is highly dependent on build orientation, loading direction, and layer thickness.
- Significant research should be conducted on the effect of porosity and the air gap on the mechanical properties of the samples manufactured in the FDM process.
- In reality, the FDM fabricated parts have anisotropic material properties. Therefore, the researchers should keep that in mind while designing FE models.
- Surface quality and geometric errors of the samples manufactured in FDM process are the least explored in the existing literature. Hence, only a handful of errors have been found. Moreover, there is no FE model on the analysis of geometrical error and surface finish of FDM fabricated parts in the existing literature. The researchers should concentrate on this topic.
- The FDM process is a transient process for quick phase transitions. Therefore, thermal stress is dominant in the parts. It is a major reason for poor part quality. Hence, more research should be conducted to reduce the temperature gradient in FDM parts.
- The temperature gradient is maximum at the tool path turning points, which is experimentally and numerically verified in the studies. Researchers should keep that in mind while doing the FEA of FDM fabricated parts.
- Macro-scale FE models and selective mesh coarsening [94] should be applied to the FEA of FDM parts. These techniques are generally used in the FEA of metal AM processes.
- To make the FE models more realistic, the researchers should include the Gaussian heat source model and Goldark's Double Ellipsoid Heat Source [47,95] in the thermal analysis of FDM parts.
- More research works should be performed to incorporate realistic boundary conditions and environmental parameters in the existing FE models to increase prediction accuracy. New materials other than only thermoplastics should be introduced in FDM research. Especially, the researchers should include reinforced thermoplastics in their FE models as they are now used by the researchers for FDM. Cloud-based parallel computing and proper knowledge management system should be introduced in FE research on FDM to reduce computational time and getting better results.

There are some limitations in the current study. The chemical, electrical and magnetic properties and topology optimization of FDM parts are not considered in this paper. Only FE simulations are presented in this paper. Comparison of FE simulations and other types of numerical simulations are not presented in this paper. Also, the paper does not contain any comparison of different meshing techniques.

One of the challenges of FE modeling of FDM parts is balancing between accuracy and computational efficiency. In the coupled thermo-mechanical analysis, the degree of freedom is higher than uncoupled analysis. Hence, the computational efficiency of coupled analysis is lower than uncoupled analysis. However, coupled thermo-mechanical analysis has better accuracy than uncoupled analysis. Selecting the correct meshing technique is another challenge for FEA.

FE analysis and other simulation techniques in AM can help the manufacturer produce eco-friendly and high-quality parts in the lowest possible time through selecting the optimized process parameters. It can help the manufacturers from wasting several scraps of material. Therefore, more FE analysis of AM techniques should be performed, especially, FDM process, as it is the least explored in existing FE literature despite its high popularity. The FE analysis of the FDM process should be extended to other materials like low melting point alloys, and difficult to machine materials like Inconel alloy. The researchers' should also concentrate on research on combined thermal, mechanical, and geometrical error analysis to create more realistic FE models.

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