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# Fused deposition modelling: a review

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**Abstract**

**Purpose** – Fused deposition modelling (FDM) is the most economical additive manufacturing technique. The purpose of this paper is to describe a detailed review of this technique. Total 211 research papers published during the past 26 years, that is, from the year 1994 to 2019 are critically reviewed. Based on the literature review, research gaps are identified and the scope for future work is discussed.

**Design/methodology/approach** – Literature review in the domain of FDM is categorized into five sections – (i) process parameter optimization, (ii) environmental factors affecting the quality of printed parts, (iii) post-production finishing techniques to improve quality of parts, (iv) numerical simulation of process and (iv) recent advances in FDM. Summary of major research work in FDM is presented in tabular form.

**Findings** – Based on literature review, research gaps are identified and scope of future work in FDM along with roadmap is discussed.

**Research limitations/implications** – In the present paper, literature related to chemical, electric and magnetic properties of FDM parts made up of various filament feedstock materials is not reviewed.

**Originality/value** – This is a comprehensive literature review in the domain of FDM focused on identifying the direction for future work to enhance the acceptability of FDM printed parts in industries.

**Keywords** Additive manufacturing, Process parameters, Fused deposition modelling, Responses

**Paper type** Literature review

## 1. Introduction

Additive manufacturing (AM) is considered a method of joining materials to create components after computer-aided-design (CAD) modelling of a part, layer-by-layer. The basic principle that drives nearly all AM machines is the creation of the virtual solid model, then breaking down this model data into series of two-dimensional (2D) cross-sections and transferring these broken data to AM machine, so that it can be combined layer by layer to develop the physical part (Gibson *et al.*, 2010). AM techniques are broadly classified as (from ISO/ASTM standard 52900:2015) (Li *et al.*, 2018):

- vat polymerization (SLA);
- material jetting (Objet);
- binder jetting (3DP);
- material extrusion (ME/FDM);
- sheet lamination (LOM);
- powder bed fusion (SLM/SLS); and
- directed energy deposition (LENS).

Fused deposition modelling (FDM) was patented by Crump in 1988, who later started Stratasys Corporation in 1989, which has a simple basic aspect but is able to manufacture complex geometries. It is a melt extrusion AM process where a feedstock filament is provided by the device which is controlled by an electric motor as shown in Figure 1.

Heated liquefier melts the filament. The liquefier/print head assembly is moved over a platform via stepper motors. The melted filament is pushed through the liquefier towards the nozzle and the nozzle deposits this melt along the XY plane on the platform (fixtureless worktable). The platform moves down or print head moves up along the Z direction by exactly one layer thickness after the completion of deposition at the successive cross-section. Thus, the three-dimensional (3D) structure is created in a layer-by-layer routine. This process continues until the part is built. At the start of the FDM process, there is an accumulation of material alongside the edge of the part and then at the internal region of the outline. A specific amount of outlines is required to pack the part as per the response required (Kai, 1994; Turner *et al.*, 2014).

The mechanism of fusion in the FDM process depends upon time taken for solidification. Fibres originally interact with each other while one of them is in a molten condition. This creates a bond between them. Fast freezing of the molten fibre might yield solidification earlier to fusion with other fibres. This creates voids among the fibres. Thus, bonds are created that do not have mechanical properties similar to a conventional manufacturing process part. The practice of FDM technique as a production method is rising day by day, but one of the greatest tasks in manufacturing FDM parts for final applications is forecasting the mechanical properties of the

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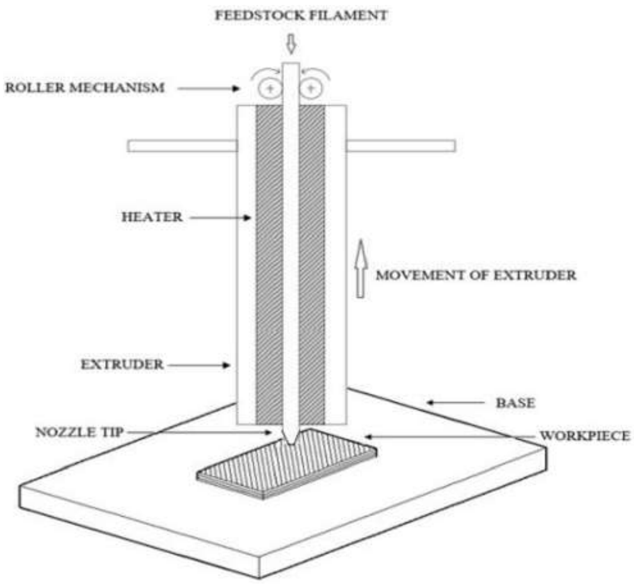
**Figure 1** Fused deposition modelling process




parts because of the discontinuous nature of the process (Coogan and Kazmer, 2017).

There are numerous applications of FDM in many fields (Negis, 2009; Korpela *et al.*, 2013; Okwuosa *et al.*, 2016; Bayar and Aziz, 2018). Lam *et al.* (2002) developed a distinguishing mixture of starch-based polymer dust (corn starch, dextran and gelatine) as a FDM feedstock. Also, they have printed and post-processed cylindrical scaffolds of developed polymer to enhance the mechanical and chemical properties. Lee *et al.* (2004) created a standard model to evaluate the FDM process for producing investment casting models. Formula society of automotive engineers (SAE) automobile intake manifold was manufactured using the FDM technique (Ilardo and Williams, 2010). Electrically conductive plastic patterns are manufactured by FDM (Monzon *et al.*, 2010). Espalin *et al.* (2010) explored the use of biocompatible poly-methyl-methacrylate in FDM to produce spongy customized freeform structures such as craniofacial reconstruction and orthopedic inserts. Diegel *et al.* (2011a) developed curved-layer FDM to produce components with conductive plastic electronic circuits. Bio-plotter based on fused filament fabrication (FFF) technology is used to print scaffold for organ printing and tissue engineering. Also, the fabrication of dental repairs is possible using the FDM technique (Van Noort, 2012). Brooks *et al.* (2012) created personalized lamps using image processing and FDM. Korpela *et al.* (2013) tested the usability of a poly (e-caprolactone)/bioactive glass mixture to inspect the creation of decomposable porous scaffold structures. Xu *et al.* (2014) used computed tomography-guided FDM to manufacture polycaprolactone/hydroxyapatite artificial bones to imitate goat femur. Durgun (2015) produced sheet metal forming dies using the FDM technology. Also, they produced sheet metal parts and assessed their quality by optical measurement methods. Petropolis *et al.* (2015) produced 3D printed models for maxillofacial surgery by FDM. Also, they compared the precision of parts made by FDM with the part made by an industrial-grade SLS printer. Pei *et al.* (2015) investigated the adhesion of polymer materials such as acrylonitrile butadiene styrene (ABS), poly-lactic acid (PLA) and nylon, printed directly onto fabrics using FDM for textile application. Šljivić *et al.* (2016) performed osteotomy surgery using FDM and poly-jet printing along with finite element analysis (FEA) simulation and modelling. Melocchi *et al.* (2016) produced filaments based on insoluble, promptly soluble, enteric soluble and swellable/erodible polymers for printing capsules in the pharmaceutical business. Zhang *et al.* (2016) presented a cross-breed mechanism of electro-hydro-dynamic jet printing and FDM technique to fabricate high-resolution scaffold structures made of PLA for tissue engineering. Boschetto *et al.* (2016) used CNC machining for the finishing of FDM parts. Corcione *et al.* (2018) demonstrated the suitability of Lecce stone waste as a stuffing for bio-composite polymer for 3D printing of ornamental industrial objects. FDM technique in the sports industry is at the nascent stage having limitations such as low range of machinable material and inefficiency in mass production; still, promising endeavors are made in this direction (Meier *et al.*, 2018). Composites are combined with a polymer matrix to achieve functional strength requirement of parts (Moldovan *et al.*, 2018). Garcia-Garcia and Gonzalez-Palacios (2018) presented a methodology for geometric design and production of industrial grade bevel gears having exact spherical involute (ESI) with variable surface details. Chougule *et al.* (2016) developed a procedure for the imitation of patient-specific bone and fabrication of respective grafts by using reverse engineering for surgical purpose. Colpani *et al.* (2018) produced a device for cleft lip and palate (dental field) and an acoustic prosthesis of biocompatible silicone by FDM. Juneja *et al.* (2018) printed surgical guides for dental application with different technologies like material jetting technology, vat photo-polymerization and material extrusion, for assessing the capability of each process to produce parts with the highest accuracy. Soriano-Heras *et al.* (2018a) developed a concept of a sectional and functioning economical prosthetic hand using shape-memory-alloy actuator and FDM. Okwuosa *et al.* (2018) produced immediate release tablets of polyvinyl-pyrrolidone, for instant, on-demand patient-specific individualized dosage via the FDM process.

As the original FDM patent has perished, a huge number of low-cost FDM printers have become available from a number of originators, and attention in this process has increased. Thus, increased applications demand FDM part quality and performance to be outstanding. Numerous researchers worldwide contributed in this since FDM inception till date; therefore, it is essential to concise this abundant amount of information, to give guidelines to FDM part producers about building part efficiently as per response required and to give research directions to the future generation. This paper is an effort in this direction.

Some researchers have reported literature review on FDM. For example, Turner *et al.* (2014) reviewed literature related to process design and modelling of FDM. Approaches for assessing motor torque and power, the model spread of deposited raster and bonding of raster are reviewed. Popescu *et al.* (2018) reported literature review related to various feedstock materials and their static mechanical properties. Literature review related to characterization and prediction of mechanical properties of FDM parts by computational and analytical methods is reported by Cuan-Urquizo *et al.* (2019). However, till date, no literature review has been reported covering most of the aspects of FDM, including numerical simulation, process parameter optimization and post-production finishing techniques.

In the present paper, research efforts made by worldwide researchers in the domain of optimization of process parameters of FDM, environmental factors affecting the performance of FDM parts, post-production finishing techniques, numerical simulation and recent advances in FDM are reviewed. Section 2 of this paper describes the proposed methodology of literature review. Section 3 discusses the literature related to FDM part quality and performance improvement. Statistical analysis is presented in Section 4. Scope of future work is discussed in Section 5, and finally, concluding remarks are given in the last section.

## 2. Proposed methodology of literature review

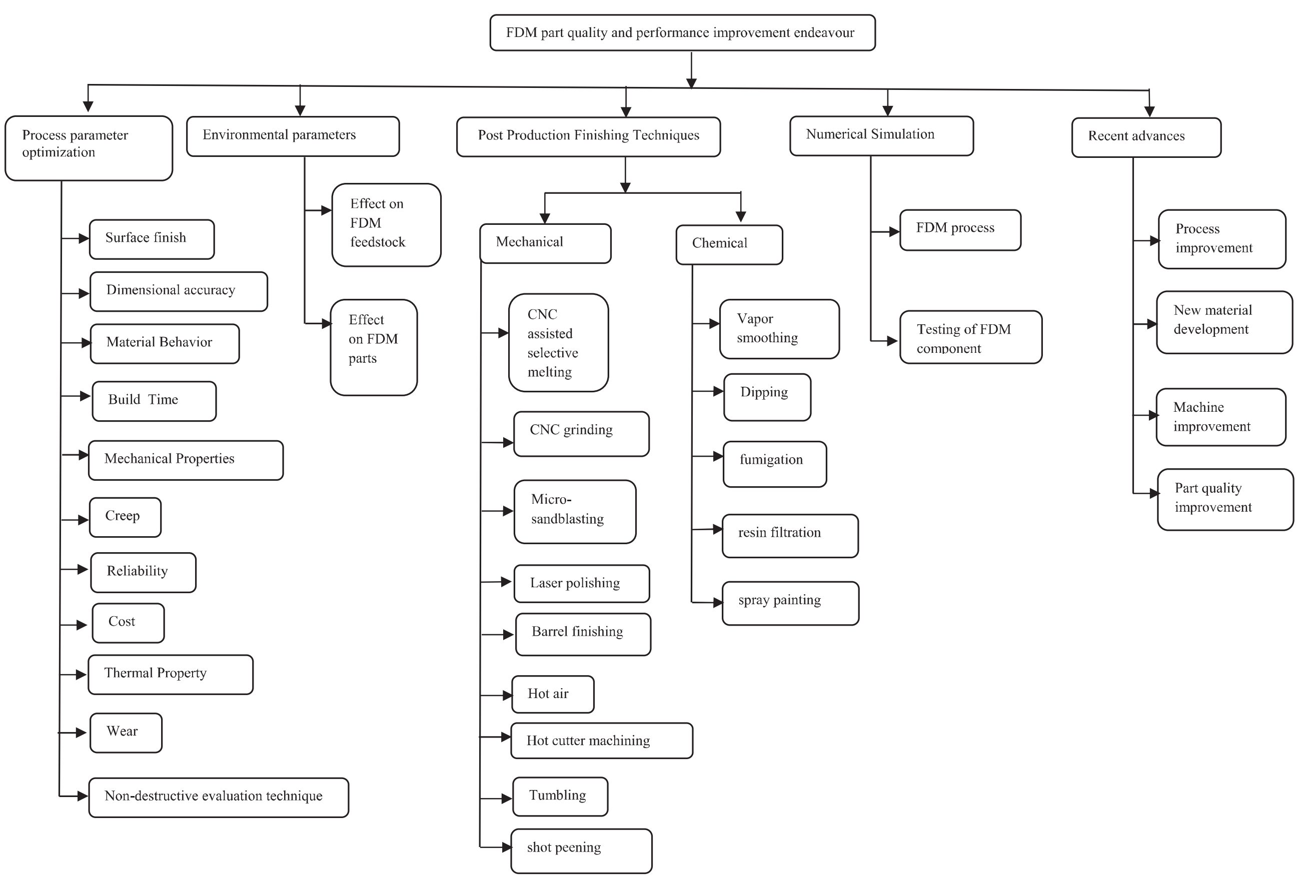
The proposed methodology of literature review on FDM is shown in Figure 2. Literature related to the optimization of process parameters is categorized on the basis of responses including surface finish, dimensional accuracy, material behaviour, build time, static and dynamic mechanical properties, creep, build cost, thermal properties, wear and non-destructive evaluation technique. Environmental parameters such as temperature and humidity have a profound impact on feedstock filament as well as fabricated part. Therefore, literature related to the study of the effect of environmental parameters on feedstock filament and fabricated part is reviewed. Post-production finishing techniques (PPFTs) of fabricated parts are essential to get finished components. Available literature related to PPFTs is reviewed by categorizing into mechanical finishing techniques, chemical finishing technique, laser polishing and sterilization methods. Numerical simulation aids in simulating real the FDM process and deciding optimized geometry of the part to be manufactured. Literature related to the numerical simulation of the FDM process and testing of FDM fabricated parts is reviewed. Finally, articles focused on recent advances such as process development, new material development, machine improvement and part quality improvement are reviewed.

## 3. Fused deposition modelling part quality and performance improvement

### 3.1 Optimization of fused deposition modelling process parameters

Most of the investigation on the optimization of FDM process parameters is focused on improving build time, surface finish, dimensional accuracy and static mechanical properties, such as compressive strength, tensile strength, impact strength and flexural strength. Research efforts on responses such as dynamic mechanical properties such as viscoelastic properties, morphological properties and reliability are increasing nowadays (Agarwala *et al.*, 1996; Vasudevarao *et al.*, 2000;

**Figure 2** Categorization of a literature review on fused deposition modelling part quality and performance improvement techniques



Anitha *et al.*, 2001; Rodríguez *et al.*, 2001; Bellini and Güçeri, 2003; Masood and Song, 2004; Wang *et al.*, 2007; Chung Wang *et al.*, 2007; Raut *et al.*, 2014; Hwang *et al.*, 2015; Meng *et al.*, 2017; Mohamed *et al.* (2016a); Mohamed *et al.*, 2017a; Mohamed *et al.*, 2017b; Aliheidari *et al.*, 2017; Keleş *et al.*, 2017). However, limited literature is available on process parameter optimization related to thermal, chemical and magnetic properties enhancement for various filament materials (Sun *et al.*, 2008; Gurrala and Regalla, 2014; Singh Boparai *et al.*, 2016; Jo *et al.*, 2018).

Agarwala *et al.* (1996) classified process parameters as process-oriented (envelope temperature, layer height, bead width, extrusion speed, extrusion temperature and raster fill pattern), machine-oriented (filament diameter, nozzle diameter, flow rate, filament feed rate and roller speed), material-oriented (thermal conductivity, viscosity, flexibility and stiffness) and geometry-oriented (fill vector length). They described the nature and origin of surface and internal defects of FDM parts of ceramics and metals and discussed novel strategies for the elimination of these defects.

Process parameters of FDM are optimized based on the response requirement. The following subsection describes the literature in this domain.

*3.1.1 Surface finish*

AM model is made from CAD models by standard tessellation language conversion, which is fed to an AM machine. Therefore, the curve in the model is converted into line according to the resolution selected. Thus, there is an approximation in input CAD modelling itself, which is translated into the final product. Vasudevarao *et al.* (2000) have found layer height and build orientation as important elements. The layer thickness was found as the most influential process parameter, and as its value increases, surface roughness decreases (Anitha *et al.*, 2001). Byun and Lee (2006) presented a model to decide the ideal part orientation for constructing a complicated part considering three responses, namely, surface finish, build time and part cost with the help of multi-criterion decision-making method. Wang *et al.* (2007) optimized process parameters by combining the Taguchi method and gray relational analysis. The most influential parameter found is layer thickness. Ahn *et al.* (2009) investigated the theoretical and actual qualities of surface roughness scatterings. Bakar *et al.* (2010) showed that circular shapes were less accurately fabricated by machine because of the restriction to head movement by gantry mechanism. Significant process parameters were internal raster, layer thickness and contour width. Durgun and Ertan (2014) found that part orientations and raster angle were affecting surface roughness. Results showed a close relationship between surface finish, with build direction. Armillotta and Cavallaro (2017) proposed an empirical model to forecast the existence of visible imperfections on the edges of a part before manufacturing it with a given build orientation (Armillotta *et al.*, 2017a). Alsoufi and Elsayed (2017) investigated the influence of factors on the surface finish of parts made up of PLA+ material and found that layer height and nozzle diameter were significant in terms of part surface roughness. They further compared the quality of surface roughness of FDM by various feedstock filament materials as PLA+, PLA, ABS+ and ABS. PLA+ showed excellent surface behaviour, while ABS showed high surface roughness for the same process parameter setting (Alsoufi and Elsayed, 2018).

From the review of available literature, it is found that layer height is the most noteworthy parameter affecting the surface finish. The decrease in its value improves surface finish, but build time and resultant build cost increases. So optimized layer thickness value should be selected considering all other responses. Build orientation and nozzle diameter has a second level of significance. But it is unsafe to rely upon process parameter optimization for achieving required surface finish; therefore, in this situation, post-production finishing techniques as described in Section 3.3 are beneficial.

*3.1.2 Dimensional accuracy*

Dimensional accuracy is essential for fit and finish requirements in an assembly. As the FDM process involves heating and cooling cycles, dimensional accuracy of fabricated part deviates from the CAD model. Armillotta (2006) provided recommendations to predict the deviation in textures, which is helpful to identify process limitation. This ensured savings in time and cost as contrasted to PPFTs. Wang *et al.* (2007) reported that the build orientation is the most significant process parameter affecting dimensional accuracy. Sood *et al.* (2010) found that the dimensions of the FDM fabricated part are more in the Z-axis, while lesser in the X- and Y-axis when compared with the CAD model of the component. Chang and Huang (2011) investigated the effect of process parameters on extruding aperture and profile error of the parts by the image measurement method. Contour width was found to be the most significant process parameter. Dani *et al.* (2013) performed multi-objective optimization of process parameters, namely, build material, support material, number of layers and build time for optimal part orientation to get best dimensional accuracy. Sahu *et al.* (2013) compared experimental results of dimensional deviation of FDM-produced ABS parts with fuzzy decision-making logic. The results of the predicted model are in correlation with experimental data with the average percentage error of less than 4.5. Boschetto and Bottini (2014) developed a geometrical model of the filament, depending upon the layer height and raster angle to predict the part dimension. Peng *et al.* (2014) converted three responses, namely, build time, warp deformation and dimensional accuracy into one comprehensive response by using the fuzzy interface system. After conducting experimental design, layer thickness and filling velocity were found to be significant process parameters.

Boschetto and Bottini (2016) have developed a design for manufacturing methodology to improve the dimensional accuracy of FDM-produced parts. This was done by balancing part surfaces with a magnitude equal to the estimated value of the proposed model. Mohamed *et al.* (2016b) proposed I-optimality criteria for the optimization of FDM process parameters. Anusree *et al.* (2017) studied the effect of controlling factors on tensile strength, dimensional accuracy and surface roughness of helical surface of a FDM-fabricated part. Ideal parameter setting was obtained by grey relational analysis. Milde *et al.* (2017) compared the shrinkage in X, Y and Z directions for a part made of ABS and PLA material. By scanning the components, more shrinkage was observed in ABS parts than PLA. Armillotta and Cavallaro (2017) provided an experimental estimation of geometric errors on the edges of parts manufactured by FDM. Mohamed *et al.* (2018) examined the stability of dimensions of FDM parts using gage repeatability and reproducibility approach. They concluded that the FDM technique is capable of producing highly accurate parts. Al-Ahmari *et al.* (2018) examined the individual effect of factors on dimensional accuracy. Factors like build orientation, extrusion temperature and layer thickness are found to be significant. They recommended that for good dimensional accuracy in a specific direction, the critical dimension must be parallel to the slice thickness, with minimum extrusion temperature and slice height. Eiliat and Urbanic (2018) presented an ideal tool-path for the FDM process to diminish discontinuities and voids by optimizing variables, such as layer thickness, raster angle, road width and air gap. Singh (2018) recommended strategies to prevent warpage of ABS and PLA parts by different ways. Best way among all methods was the treatment of bed with PVA-based solution which was inexpensive and environment-friendly. Also, the use of Kapton tape was impressive to prevent warpage than bed treatment with ABS-acetone solution. Vishwas *et al.* (2018) manufactured components from ABS and nylon material and concluded that build orientation and layer thickness were the most influential factors. Armillotta *et al.* (2018) observed that an increase in layer thickness has a decisive effect on warpage because it makes the part more resistant to bending. Also, thin parts show less distortion compared to thick parts (Armillotta *et al.*, 2017). Mahmood *et al.* (2018) showed that the number of shells remained the utmost influential factor. Haghighi and Li (2018) observed that building orientation in the Z-direction was found to be significant because it reduces fill density, cost and dimensional variation.

From the review of available literature, it is found that the accuracy of FDM is affected by uneven shrinkage and residual stress within the part. Build orientation, layer height and number of outlines are found to be the most significant process parameter trailed by extrusion temperature and layer height. Air gap and raster angle were found to be insignificant for dimensional accuracy (Dawoud *et al.*, 2016).

#### *3.1.3 Material behaviour*

Recent efforts are made in studying the behaviour of feedstock material of better mechanical properties as compared to the polymer. Perez *et al.* (2014) discovered that ABS reinforced with 5 per cent by weight titanium dioxide demonstrated the highest ultimate tensile strength (UTS) for specimens built in both horizontal and vertical directions. Hwang *et al.* (2015) developed ABS-Fe and ABS-Cu filaments and assessed the thermal and mechanical properties of the part by varying the metal content and factors such as print temperature and fill density. Tensile properties decrease and thermal conductivity increases with an increase in the metal content. Tensile strength decreases with the fill density and viscosity of ABS being extruded. Weng *et al.* (2016) showed that the addition of 5 weight percentage organically modified montmorillonite (OMMT) improved the tensile strength of FDM ABS samples by 43 per cent. Addition of OMMT considerably increased the flexural strength, flexural modulus, tensile modulus and dynamic mechanical properties and decreased the linear thermal expansion ratio for FDM as well as injection molded specimen. Ning *et al.* (2016) showed that carbon fibre reinforced polymer (CFRP) composite specimen fabricated with 5 per cent weight carbon fibre can act as a load-bearing structure in the assembly which was not possible previously with the use of only polymer feedstock. Nozzle temperature, infill speed and the layer thickness were found to be significant considering tensile properties. Navarrete *et al.* (2017) studied mechanical and thermal characteristics of FDM parts made of biocomposites. Samples with 20 per cent wood flour showed lower tensile strength and flexural strength. From the thermogravimetric analysis, the optimum temperature for the printing of composites was found. Meng *et al.* (2017) examined the effects of the addition of the nanoparticles on the mechanical strength, anisotropy and thermal properties. Tensile and flexural strength is increased by 25.1 and 17.1 per cent, respectively, using montmorillonite addition. Gardan *et al.* (2018) studied the fracture behaviour of specimens made by newly developed filament deposition criteria (stress-based criteria). Improvement is observed in strain concentration zone and crack extension. In all, 30 per cent improvement in fracture toughness was observed. Osman and Atia (2018) developed new composite filament (ABS + rice straw) for the FDM process and checked the variation in the tensile strength, flexural strength and weight change according to the variation in the content of rice straw in ABS. Tensile properties and flexural properties decrease with an increase in rice straw. Caminero *et al.* (2018a) evaluated the influence of layer thickness and volume content of fibre on inter-laminar binding performance of carbon, glass and Kevlar fibre-reinforced nylon composites fabricated by the FDM process. They found that the layer thickness had marginal significance on inter-laminar shear performance and carbon fibre-reinforced composite exhibited best inter-laminar shear performance with good stiffness. Jiang *et al.* (2019) used polyetherimide as a filament, having high glass transition temperature and good mechanical properties. Researchers investigated dynamic material properties at 370°C nozzle temperature; mean tensile strength of FDM parts was observed to be just 7 per cent lower than that of injection molded parts. Impact strength result pattern also shows similar results as tensile strength results.

Addition of reinforcing materials improves mechanical properties of polymer material; however, scarce literature is available regarding its effect on thermal, electric and magnetic properties. Also, further improvement is required in the development of nozzle for metal extrusion, heat shielding of the chamber for sufficient heat entrapment to melt as well as bond metal layers (as metals have high melting point than polymer, and also, there will be rapid heat flow to the neighboring environment if sufficient insulation is not provided).

#### *3.1.4 Build time*

Thrimurthulu *et al.* (2004) proposed a methodology to use a multi-criteria genetic algorithm that was further used to decide best build orientation for the freeform part. Ghorpade *et al.* (2007) presented the advanced swarm intelligence approach for optimal orientation of the part to reduce build time. With this approach, enhanced orientation efficiency, minimized volumetric error and minimized build time were found. Espalin *et al.* (2014) investigated the build process deviation using different road width and layer thickness. They also examined the influence of build process variation on production time. This resulted in a 53 per cent reduction in build time. Peng et al. (2014) showed that layer height and filling velocity were found to be significant if build orientation was kept constant.

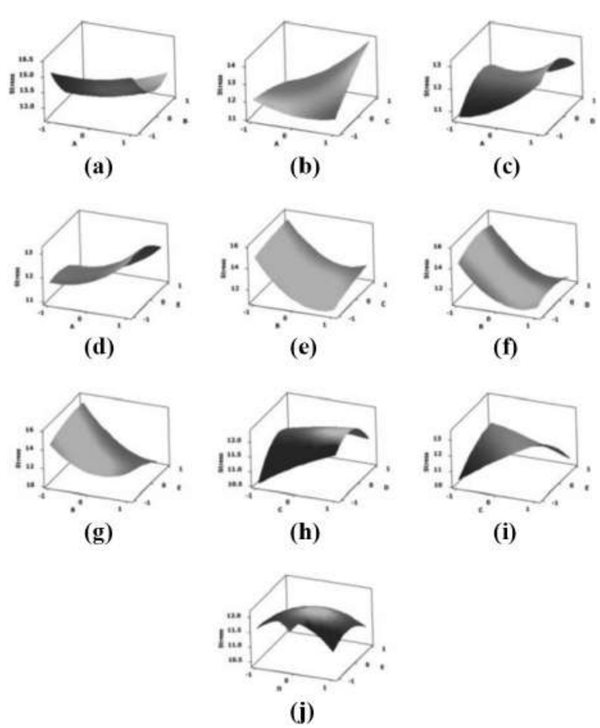
From the review of available literature, it is found that layer height, filling velocity (velocity of nozzle movement along the XY plane) and build orientation are influential parameters for build time.

*3.1.5 Mechanical properties of fused deposition modelling parts*

*3.1.5.1 Static mechanical properties of fused deposition modelling part.* Abundant literature is available related to the evaluation of static material properties of the FDM part of various materials. Too et al. (2002) investigated the influence of factors on the pore diameter, porosity and compressive strength of the porous shapes. A model was developed for the prediction of the consequence of the air gap on the porosity of the structure. Ahn et al. (2002) observed that for parts made of overlap (negative air gap), the tensile strength was observed to be 65-72 per cent of the injection molded part. The compressive strength of FDM ABS parts was observed to be 80-90 per cent of an injection molded ABS part. Thumb rules aimed at the building of FDM part for maximum part strength were provided by researchers. Bellini and Güçeri (2003) researched the influence of raster angle and part orientation on tensile strength and flexural strength using experimental and analytical approaches. Ahn et al. (2003) proposed an analytical model to forecast the tensile strength of parts manufactured by FDM according to the change in the raster angle by applying the Tsai-Wu failure criterion and the classical lamination theory. Rodrı¨guez et al. (2003) developed a mathematical model of the mechanical system based on inexact minimization algorithm to find parameters settings to improve tensile strength and stiffness. Lee et al. (2005) achieved optimized process parameters values for maximum elastic performance (throwing distance of catapult). Chin Ang et al. (2006) examined the effect of FDM factors on the porosity, compressive strength and compressive modulus of ABS tissue engineering scaffold structures. Greatest mechanical properties were observed in small porosity frameworks. Wang et al. (2007) observed 90.45 per cent increase in tensile strength with the optimization of process parameters. Deposition orientation was found to be the most influential process parameter. Abbas et al. (2008) focused on the effect of layer height on impact properties parts produced from a PLA polymer. Optimal layer thickness value was found for impact strength. Panda et al. (2009) optimized factors for tensile, impact and flexural strength of specimen using the bacterial foraging technique. Sood et al. (2010) determined an association among process parameter and response using response surface methodology. For good strength, reduction in distortion is necessary. Optimal factor settings for tensile and flexural strength were found to be the same, but it differed in factor levels for impact strength. They further considered tensile, bending and impact strength as responses and simultaneously optimized all these responses (Sood et al., 2011). Fatimatuzahraa et al. (2011) used different raster angle orientations for evaluating mechanical properties and microstructure of FDM parts. Tensile, impact, bending and deflection tests were performed on parts manufactured with ABS material. Data analysis showed that crisscross-oriented (45°/−45°) samples had higher strength for deflection, flexural and impact tests. The tensile test result showed higher strength in cross-orientation (0°/90°). Domingos et al. (2012) investigated the impact of factors on the mechanical and morphological properties of poly-έ-caprolactone porous frameworks. Screw rotation velocity and deposition velocity had the most effect on the mechanical properties of the part. Sood et al. (2012) observed that low part strength was because of distortion and anisotropy which was minimized by careful parameter setting selection. Croccolo et al. (2013) studied effects generated by the number of contours and build orientation on the tensile strength, stiffness and Young's modulus of ABS-M30 parts, from both the experimental and the numerical points of view. Lee and Huang (2013) determined the effect of fatigue on ABS and ABS+ parts made by FDM by varying the print orientation. ABS+ part's properties were found to be isotropic than properties of ABS parts. Smith and Dean (2013) explored the effect of build orientation on tensile strength and elastic modulus of polycarbonates (PC) parts produced by FDM. It is observed that there is 45 per cent decrease in elastic modulus and 30 to 60 percent decrease in UTS of manufactured part as compared to bulk material. Ashtankar et al. (2013) executed experiments on ABS parts. They scrutinized the influence of part orientation on tensile and compressive properties. The part orientation of the sample has more impression on strength. Onwubolu and Rayegani (2014) found optimal process parameters using differential evolution. It was observed that low road width, low layer height, zero build orientation and negative air gap improve tensile strength. Stephen et al. (2013) examined the effect of factors on various mechanical properties. Combination of modulus, weight and impact strength can be used to conclude the quality of build parts. Fill pattern and build orientations and layer thickness were found to be significant process parameters. Magalhães et al. (2014) suggested that the correct choice of raster angles in sandwich-like formations can make substantial advances in the final strength and/or stiffness of parts. Tymrak et al. (2014) investigated the association between raster pattern and a layer height of open source printers to tensile strength, modulus and strain at tensile strength. Raut et al. (2014) optimized build orientation of a FDM machine for tensile, flexural strength and total cost by using the ABS material. The Y-axis at 0° build orientation delivers effective tensile strength and minimum cost. The X-axis at 0° build orientation parts have useful flexural strength and medium cost. Hossain et al. (2014) assessed improvement in strength with modifying process parameters by using three techniques, namely, visual feedback, insight revision and default method. They found that optimizing process parameters using insight revision method yielded higher UTS. Durgun and Ertan (2014) showed that small raster (0°) in the horizontal direction offered maximum strength because of larger effective raster length. Syamsuzzaman et al. (2014) compared mechanical properties of low-cost FDM machine with commercial FDM machine, by keeping the same layer thickness for ABS material. Negative air gap among neighbouring rasters in the same layer, small layer thickness, crisscross raster orientation were found to be optimum settings. Also, there is a high amount of non-linearity between process parameters and responses, as seen by curvature in response to surface plots in Figure 3. Carneiro *et al.* (2015) examined the influence of infill degree, filament orientation and layer thickness on the mechanical properties of parts made of two grades of polypropylene (PP), that is, a non-reinforced and a glass-fiber reinforced. Ziemian *et al.* (2015) considered the influence of raster angle on tensile strength and fatigue performance of ABS parts. Lanzotti *et al.* (2015) quantified UTS, elastic modulus and a nominal strain at break of PLA-printed parts by low-cost printer. The decrease in strength was observed as infill orientation comes closer to 90° and increases when perimeters increase. Senatov *et al.* (2016) examined structural qualities, mechanical properties and shape memory effect of a porous scaffold made of (PLA)/15 wt.per cent hydroxyapatite. Chockalingam *et al.* (2016) studied the dependency of factors on tensile strength and density. Dawoud *et al.* (2016) explored the effect of raster angle and air gap on tensile, flexural and impact strength of ABS parts. The negative air gap was found to be the most important process parameter for the mechanical property enhancement.

Torres *et al.* (2016) developed a combined characterization-optimization method. Less value of layer thickness and print speed results in high resolution parts. Torrado and Roberson (2016) carried out experiments to find the effect of raster pattern and build orientation on the anisotropy of the tensile strength of FDM ABS parts. Al-Ahmari *et al.* (2018) studied the individual effect of factors on the mechanical property. Mechanical properties are influenced more by building direction, layer thickness and extrusion temperature. To have good mechanical properties, larger layer thickness, higher extrusion temperature and appropriate building direction are

**Figure 3** Response surface plots



**Source:** Sood *et al.* (2012)

needed. D'Amico *et al.* (2017) observed that thermal strain increased with an increase in the layer height. Flexural strength was 18 to 41 per cent of the reported flexural strength of bulk ABS. Tensile strength was 54 to 97 per cent of the reported values of injection molded ABS. In this study, irreversible thermal expansion may cause the failure of the FDM part, but this phenomenon is controlled by changing the value of layer height. Cao and Xie (2017) proposed an orthotropic model to define the elastic constant of the part using combined the virtual fields method and digital image correlation using the configuration. Garg and Bhattacharya (2017) studied elastoplastic behaviour of parts by examining the influence of layer height and raster angle on tensile strength using experiments and finite element analysis. It was concluded that stress, strain and tensile strength decrease with an increase in layer height from 0.178 to 0.254 mm, but values of these responses increase with an increase in layer height from 0.254 to 0.33 mm.

Luzanin *et al.* (2017) investigated the result of raster angle changes on surface finish, tensile and flexural strength of FDM parts. Researchers suggested 0° is optimal raster angle value to accomplish greater mechanical strength with reduced surface finish (Garg *et al.*, 2017b; Gardan *et al.*, 2018). Tanikella *et al.* (2017) demonstrated that the tensile strength of a FDM sample depends on the mass of the specimen. Alaimo *et al.* (2017) found that the mechanical properties of parts produced were anisotropic, as they change according to the filament extrusion direction. Elastic modulus increased while increasing the filament section, both at 0° and 90°. Stiffness increases with bigger filaments. The reverse is true for UTS and shear strength at 0°, that is, an increased number of small cross-section roads exhibit more strength. Diaconescu *et al.* (2017) showed that the parts manufactured using a 45°/45° raster pattern were stronger than the ones manufactured using 0°/90°. Cantrell *et al.* (2017) performed experiments to tensile and shear descriptions of ABS and PC FDM parts by varying the raster and build orientations to decide the directional properties of materials. Santana *et al.* (2017) analysed the factors disturbing the deposition quality of parts made of PLA with differences in extrusion temperature and print speed. Samples were examined through mass measurements, optical microscopy and flexural tests. Uddin *et al.* (2017) compared the mechanical properties of the FDM part with injection molded parts. FDM component layers adjust themselves followed by extending before fracture failure, thus delivering more ductility than injection molded parts. Layer thickness and build orientation were found to be significant factors. Mahmood *et al.* (2017) showed a reverse relation between part scalability, change in cross-sectional area and UTS of FDM-manufactured parts. Chacón *et al.* (2017) characterized the effect of orientation, layer height and feed rate on the mechanical performance of PLA samples fabricated by the FDM process. They found that the upright orientation results in lesser strength and stiffness as compared to on-edge and flat orientation of FDM-fabricated parts. It was also observed that mechanical properties of part increase with the increase in layer thickness and decrease in feed rate.

Rohde *et al.* (2018) found that the ABS specimens demonstrated anisotropy as a function of build orientation and PC specimens exhibited anisotropy as a function of raster orientation. Gomez-Gras *et al.* (2018) observed that fill density was the most prominent process parameter followed by nozzle diameter and layer thickness on fatigue life. Taylor *et al.* (2018) studied the consequence of build orientation and raster angle on flexural strength of parts made of ULTEM 1010 (unfilled polyetherimide – a semi-transparent high strength material) material experimentally and numerically. Gebisa and Lemu (2018) found that the raster width and raster angle had the maximum effect on the flexural properties of ULTEM 9085 components. Balderrama-Armendariz *et al.* (2018) performed experiments to study the effect of factors on ultimate shear strength, 0.2 per cent yield strength, fracture strain and shear modulus. FDM specimens were similar to injection molded specimen in all aspect except for the fracture strain. Arif *et al.* (2018) examined the consequence of factors on tensile strength, flexural strength and fracture toughness for polyether ether ketone (PEEK) material. Fracture surface and microtomography analysis illustrated that the interfacial bonding degree between layers is affected by thermal gradient across beads. Small deposition length should be considered for the inner region of the part and long deposition length for the outer region of a part to have a better surface finish. Dong *et al.* (2018) studied the impact of process parameters on print quality, elastic modulus and UTS of the lattice structure. For a horizontal strut and an inclined strut, layer thickness and fan speed were significant process parameters, respectively. Compression tests were conducted to assess the mechanical functioning of the lattice structure. Li *et al.* (2018) used a bilinear elastic-softening cohesive zone model for analysing extreme stress that part can endure under various interference bonding state. Vishwas *et al.* (2018) observed that orientation and shell thickness were the highest significant process parameters for mechanical properties of ABS and nylon parts. Slonov *et al.* (2018) performed experiments to find the influence of factors on the mechanical properties of polyphenylenesulfone. Elastic modulus varies as the air gap changes, and it is independent of the raster angle. Impact strength depends on the orientation and the adhesion degree between the filaments. Rajpurohit and Dave (2018a) examined the effect of factors and their interaction on strain at break and UTS of parts manufactured by open source FDM printer. The tensile test showed that 0° raster angle exhibit greater tensile strength than 90°. Fractography was performed using a high precision optical microscope to finalize the influence of factors on the mode of failure. The close-fitting connection between raster angle and mode of failure was observed. Further, they investigated the effect various factors have on flexural properties of PLA parts manufactured by an open source FDM printer. Flexural strength reduces with the rise in raster angle from 0° to 90°, with an increase in the layer height. At the in-between value of raster width, high flexural strength was observed (Rajpurohit and Dave, 2018b). Caminero *et al.* (2018b) evaluated the effect of orientation, layer height and volume content of fibre on impact properties of glass, carbon and Kevlar fibre-reinforced nylon composite fabricated by the FDM process. Samples were examined using Charpy impact test. They found that the impact strength increases with increase in layer thickness in flat orientation samples, while it decreases in on-edge orientation samples. Also, with the increase in fibre content volume, impact strength increases. Kerekes *et al.* (2019) characterized process-deformation/damage fracture property relationship of FDM specimens. Infill density was found to be a significant process parameter.

From the review of available literature, it is found that build orientation, layer height, infill percentage, air gap (negative) and raster angle orientation (crisscross,+45°/−45°) are significant process parameters followed by extrusion temperature, number of perimeters and print speed for the improvement in static mechanical properties of the FDM part.

*3.1.5.2 Dynamic mechanical properties of fused deposition modelling part.* To simulate real-world problems, the evaluation of dynamic mechanical properties is imperative. Masood and Song (2004) developed composite filament (Nylon-6 and 30-40 per cent iron) for a FDM process and performed dynamic mechanical thermal analysis. Mohamed *et al.* (2016a) found the impact of multi-level factors on temperature-dependent dynamic mechanical properties of PC-ABS. The consequence of each factor was examined using multiple regression analysis and regression models. For storage and loss compliance, the significant parameters were air gap, layer height and the number of contours. Mohamed *et al.* (2017a) examined the influence of process parameter on dynamic mechanical properties of FDM-processed components through I-optimal design. Analysis of variance analysis showed that the response surface equation had a good fit. Dakshinamurthy and Gupta (2018) investigated the effect of factors on viscoelastic properties of ABS component. Optimum parameter settings for improving storage and loss modulus were found. The relative contribution of layer thickness (55 per cent) and raster width (31 per cent) was found on viscoelastic properties of components.

From the review of available literature, it is found that layer height, raster angle, raster to the raster air gap and the total number of perimeters are significant process parameters for the enhancement of dynamic mechanical properties.

#### *3.1.6 Creep*

Polymers are sensitive to temperature and strain rate. As most of the feedstock materials are from polymer family, it is imperative to study creep properties. Mohamed *et al.* (2017c) investigated short-range creep distortion of PC-ABS components. The optimal arrangement of parameters to diminish the creep deformation was found. The lowermost size of layer height can produce pinholes and cavities in the component. Salazar-Martin *et al.* (2018) studied the change of parameter values on the creep behaviour of FDM-PC parts. The part build orientation analysis showed the importance to organize the placed filaments in a similar direction in which the sample was pulled and the significance of the total number of outlines. Overall, YZ positioning, zero air gap and most numbers of contour provided optimum process parameter values.

From the review of available literature, it is found that layer height, raster angle, part orientation and the number of outlines have the largest influence upon creep performance, while road width and air gap have less effects on the creep property of FDM parts.

#### *3.1.7 Reliability*

Poor reliability is a major hindrance in wide acceptance of AM parts; therefore, its study is vital. Keleş *et al.* (2017) investigated dissimilarity in the fracture strength of FDM ABS specimen with and without a round hole at the center under tensile loading. Also, the impact of part orientation on the mechanical reliability of ABS parts produced using FDM was also investigated. The Weibull analysis was done to measure distinction in tensile strength. For specimen without a hole, Weibull modulus was found to lie between 26 and 69, and for a specimen with a hole, it ranges from 30 to 41. The *p*-type deviation was observed from Weibull statistics. XA orientation results in the maximum average fracture strength for a specimen with and without the hole.

#### *3.1.8 Build cost*

Dani *et al.* (2013) performed multi-objective optimization of factors for optimal part orientation to get minimum manufacturing cost. The zero degree orientation was found to be the best followed by 45°. Boschetto and Bottini (2014) developed a geometric model of the filament, depending upon raster angle and layer height to forecast part dimension that can be obtained. A profilometer analysis was performed to investigate the scattering of experimental measures. This model also suggests the process parameter value of optimizing cost, time and product quality. Raut *et al.* (2014) optimized build orientation of FDM machine for the total cost. The total cost of manufacturing includes main material cost, support material cost and built up time multiple of machine cost per unit time. Y-axis at 0° part orientation shows the minimum cost required. At X-axis at 0° part, orientation parts have a medium cost requirement. Haghighi and Li (2018) performed a comprehensive analysis of manufacturing cost (includes material cost, energy cost and operational cost). According to results, orientation in Z-direction is preferred over the XY plane. In Z-direction, reducing fill density reduces cost and dimensional variation.

From the literature review, it is found that the slice thickness, build orientation and infill density are the most significant process parameters influencing build cost.

#### *3.1.9 Thermal properties of fused deposition modelling parts*

Thermal properties of FDM parts have been studied by many researchers. For example, Masood and Song (2004) evaluated thermal properties on new metal/polymer material (nylon/iron) that was found acceptable for rapid tooling for injection molding. Sun *et al.* (2008*)* studied effect factors on the cooling qualities, mesostructure, flexural strength and overall quality of the bond strength between filaments. The production approach, the envelope temperature and differences in the convection coefficient were found to be significant process parameters. Gurrala and Regalla (2014) investigated the influence of bonding between the filaments to the strength of the components with the help of experiments and mathematical modelling. They found that the strength of the component was chiefly because of intra-layer attachment, inter-layer attachment and neck development among filaments. Also, the necessary time for the full merging of filaments is not available before complete solidification occurs, and hence, only unfinished neck growths were found to take place. Singh Boparai *et al.* (2016) studied the mass and phase change for thermal categorization of a Nylon 6-based nano-composite (NC) material by differential scanning calorimeter and thermo-gravimetric analysis. Sinha and Meisel (2018) proved that tensile properties are damaged during embedding because of the need for process disturbance. These effects can be tackled by reheating the paused layer during the FDM process. Jo *et al.* (2018) investigated the warming influence on the mechanical properties of FDM objects in terms of layer height, duration of heating and pressure with heating. Prajapati *et al.* (2018) presented the experimental measurement technique of anisotropic thermal conductivity and interlayer thermal contact resistance by varying the air-gap in FDM parts made of ABS and ULTEM. Also, an analytical model was used to predict the value of thermal conductivity for corresponding air-gaps. They reported the measurement of thermal conductivity of samples in the filament raster direction and in the build direction according to the variation in air gap.

There is a strong thermal contact resistance in build direction, which is the cause of anisotropy in parts produced. It should be accurately accounted for part design. From the review of literature, it is found that build direction, layer thickness and air gap are influential parameters for thermal properties of FDM parts.

#### *3.1.10 Wear*

Sood *et al.* (2012) performed experiments to understand the consequence of parameters on the sliding wear of a specimen. A small value of layer height, part orientation combined with the large value of raster angle reduces wear properties. Garg and Singh (2015) compared the friction and wear characteristics of the Nylon 6-Iron composite with the existing ABS filament of the FDM. Singh *et al.* (2016) investigated the effect of contact load and run time at constant sliding velocity on friction and wear behaviour of the parts made of composite material (Nylon-6, Al, $Al_2O_3$) and ABS.

#### *3.1.11 Non-destructive evaluation technique*

To achieve consistency in the quality of FDM parts, non-destructive evaluation techniques are required. This ensures the identification of surface as well as internal defects. Gajdoš and Slota (2013) showed that the structure of FDM part is altered by changing processing temperature, envelope temperature and layout on the base plate. The specimens were examined by computer tomography (CT) to evaluate the change in the layers' structure, dimensions and fraction of unfilled volume in a specimen. It was found that the structures' homogeneity was affected by the shape of the fabricated part. Gajdoš *et al.* (2016) proposed a strategy for minimizing internal voids to improve mechanical properties. PC specimens with original and modified deposition strategies were analysed using metro-tomography and tensile testing. With modified tool-path, voids were reduced which resulted in increased tensile strength. Lu and Wong (2017) performed a literature review of various non-destructive testing techniques for the testing of AM parts. Applications of techniques and their appropriateness for defect detection were also reviewed. Xia *et al.* (2018a) proposed a novel magneto-Archimedes levitation technique for the non-destructive measurement of FDM parts. They found that the polymer parts maintain their equilibrium posture as per shape and size irrespective of the material. Levitation height was varying as per materials used. Caminero *et al.* (2019) used phased array ultrasonic technique to detect internal damage in composite laminated fabricated by the FDM process. Drop impact tests were performed on CFRP and 3D printed reinforced composite laminates to induce impact damage.

They found that the low-velocity impact produces widespread subsurface delamination with an increase in impact energy and thickness. However, it is challenging to evaluate manufacturing defects and internal damages in composite laminates by ultrasonic test because of high signal attenuation and distortion characteristics of the material.

On the basis of literature review related to non-destructive evaluation techniques, it is found that ultrasonic testing and CT were positive for *in situ* and post-process defect detection. CT is the only technique that produces a complete model of FDM part with internal as well as the external surface.

Based on the overall literature review, it can be concluded that optimization of process parameter of FDM process is one of the most crucial tasks for obtaining high-quality components, improved material response and superior properties. With the availability of different types of FDM machines in the market, the task of quality characteristics evaluation is more evident. It is found that part orientation, layer height, raster angle, road width, air gap, infill density, fill pattern and feed rate have an influence on the quality and performance of FDM part. Build orientation should be properly selected, as it changes failure mode from brittle to ductile. There is a minimum limit on the value of layer height. Therefore, surface roughness of parts should be dealt by using appropriate PPFT. Raster width and contour width generally vary from 1.2 to 1.5 times of nozzle diameter depending on the feedstock material. Air gap, infill density and infill pattern should be properly selected by taking into consideration the build time and strength requirement of fabricated part. Raster angle should be selected in line with loading direction to maximize strength of part. Because of the flexibility of selecting process parameter values, there is no optimal process parameter setting available for aesthetics, mechanical property, material consumption and build time for all materials. Therefore, according to the response requirement, process parameter needs to be adjusted. The available literature on the optimization of process parameters is categorized on the basis of feedstock filament materials (Table I). Summary of major research work in the area of optimization of process parameters of FDM is given in Table II.

Besides the process parameters, the quality of FDM parts also depends on environmental conditions.

## 3.2 Effect of environmental parameters

Environmental factors such as temperature and humidity affect the performance of feedstock filament as well as the quality of the FDM part. Limited literature is available in this area of FDM.

### *3.2.1 Effect of environmental parameters on feedstock filament*

Deterioration in the quality of the FDM filament because of environmental factors such as humidity and temperature is translated to the final part quality or may sometimes block the FDM nozzle itself. Halidi and Abdullah (2012) found that the reason for nozzle clogging is not a physical change in filament because of environmental factors, but maybe morphological and thermal stability change, in which further investigation is required.

### *3.2.2 Effect of environmental parameters on the fused deposition modelling part*

Kim *et al.* (2016) found that the tensile strength of FDM part in dry and room temperature conditions was 26-56 per cent of an injection molded parts as per part orientation. Also, heightened temperature and water absorption have more effect on FDM parts than on injection molded parts. Leite *et al.* (2018) examined the influence of sealing treatment on mechanical properties and water absorption of FDM parts printed with ABS. Aqueous acrylic-based varnish conserved dimensional stability, reduced open porosity and preserved mechanical properties of the specimen.

From the literature review related to the effect of environmental parameters, it can be concluded that augmented temperature and water absorption had a more substantial influence on FDM parts than injection molded parts because of air cavities inside the parts. Therefore, more study is required in the direction of minimizing air cavities by precise deposition control of rasters, that is, research on feedback system by using the sensor to check the presence of air cavities and in the direction of sealing properties improvement to enhance the durability of FDM part.

## 3.3 Post-production finishing techniques (PPFTs)

Because of the exhaustive energy, fast cooling and phase transformations, parts manufactured by FDM deviate from the intended geometry, and some parts need lengthy post-processing. Therefore, post-production finishing is required to make commercial FDM parts.

### *3.3.1 Mechanical finishing technique*

Pandey *et al.* (2003a) used hot cutter machining to improve surface roughness. The improvement was observed in the surface finish of class of 0.3 $\mu$m with 87 per cent confidence level. Taufik and Jain (2016) used CNC assisted selective melting tool to increase surface finish of FDM parts. Singh and Trivedi (2017) explored the effect of a barrel finishing process in the improvement of surface finish and dimensional accuracy of FDM parts. It was found that the surface roughness is significantly influenced by the shape of barrel finishing media and parts layer density. Adel *et al.* (2017) used hot air to melt microscopic corners to reduce staircase surface. Reduction in $R_a$ value of 88 per cent was recorded. Lavecchia *et al.* (2018) compared the effect of two PPFTs, computer numerical control (CNC) grinding and micro-sandblasting on the surface roughness of the FDM part. Further, they used a physical vapor deposition process on each type of parts to apply a thin metal film over the surface. Results showed that CNC grinding process is better than micro-sandblasting for surface finishing improvement.

From the literature review, it can be concluded that the CNC grinding technique of surface finish improvement is best among other mechanical methods. But its use is limited to simple geometries.

### *3.3.2 Chemical finishing technique*

Non-contact finishing techniques like chemical finishing technique have a profound impact on the surface roughness of FDM parts. Galantucci *et al.* (2009) examined the influence of chemical treatment on the FDM part and found that there is a significant enhancement in the surface finish with a slight

**Table I** Categorization of available literature related with optimization of process parameters on the basis of feedstock filament materials

| Material | Researcher |
|---|---|
| ABS | Vasudevarao *et al.* (2000), Anitha *et al.* (2001), Rodríguez *et al.* (2001), Ahn *et al.* (2002), Too *et al.* (2002), Ahn *et al.* (2002), Rodrı¨guez *et al.* (2003), Rodríguez *et al.* (2003), Ahn *et al.* (2003), Bellini and Güçeri (2003), Lee *et al.* (2005), Armillotta and Cavallaro (2017), Chin Ang *et al.* (2006), Armillotta (2006), Wang *et al.* (2007), Sun *et al.* (2008), Panda *et al.* (2009), Ahn *et al.* (2009), Sood *et al.* (2010), Bakar *et al.* (2010) Anusree *et al.* (2017), Sood *et al.* (2011), Chang and Huang (2011), Fatimatuzahraa *et al.* (2011), Lee and Huang (2013), Sood *et al.* (2012), Sood *et al.* (2012), Dani *et al.* (2013), Sahu *et al.* (2013), Croccolo *et al.* (2013), Ashtankar *et al.* (2013), Espalin *et al.* (2014), Durgun and Ertan (2014), Peng *et al.* (2014), Raut *et al.* (2014), Onwubolu and Rayegani (2014), Syamsuzzaman *et al.* (2014), Boschetto and Bottini (2014), Tymrak *et al.* (2014), Magalhães *et al.* (2014), Perez *et al.* (2014), Chockalingam *et al.* (2016), Ziemian *et al.* (2015), Garg and Singh (2015), Meng *et al.* (2017), Garg *et al.* (2016), Dakshinamurthy and Gupta (2018), Torrado and Roberson (2016), Dawoud *et al.* (2016), Mahmood *et al.* (2017), D'Amico *et al.* (2017), Keleş *et al.* (2017), Rohde *et al.* (2018), Armillotta *et al.* (2017), Diaconescu *et al.* (2017), Leite *et al.* (2018), Tanikella *et al.* (2017), Uddin *et al.* (2017), Milde *et al.* (2017), Armillotta and Cavallaro (2017), Garg *et al.* (2017b), Gardan *et al.* (2018), Tanikella *et al.* (2017), Garg and Bhattacharya (2017), Mahmood *et al.* (2017), Mahmood *et al.* (2018), Haghighi and Li (2018), Dong *et al.* (2018), Balderrama-Armendariz *et al.* (2018), Chohan and Singh (2017), Eiliat and Urbanic (2018), Vishwas *et al.* (2018), Prajapati *et al.* (2018), Singh *et al.* (2018), Alsoufi and Elsayed (2018) |
| ABS+ | Lee and Huang (2013), Alsoufi and Elsayed (2018) |
| PLA | Tymrak *et al.* (2014), Lanzotti *et al.* (2015) ,Torres *et al.* (2016), Abbas *et al.* (2008), Milde *et al.* (2017), Luzanin *et al.* (2017), Santana *et al.* (2017), Li *et al.* (2018), Rajpurohit and Dave (2018a), Rajpurohit and Dave (2018b), Gomez-Gras *et al.* (2018), Jo *et al.* (2018), Singh *et al.* (2018), Alsoufi and Elsayed (2018) |
| PLA+ | Alsoufi and Elsayed (2018) |
| PC | Smith and Dean (2013), Hossain *et al.* (2014), Boschetto and Bottini (2014), Dakshinamurthy and Gupta (2018), Rohde *et al.* (2018), Tanikella *et al.* (2017), Salazar-Martin *et al.* (2018) |
| PC-ABS | Mohamed *et al.* (2016a, 2016b), Dakshinamurthy and Gupta (2018), Mohamed *et al.* (2017b), Cantrell *et al.* (2017), Bartolai *et al.* (2018) |
| Nylon | Tanikella *et al.* (2017), Vishwas *et al.* (2018) |
| Nylon6—Fe composite | Garg and Singh (2015) |
| ABS + iron composite | Nikzad *et al.* (2009) |
| ABS+ Fe, ABS+ Cu | Hwang *et al.* (2015) |
| ABS composite (Nylon-6, Al, $Al_2O_3$) | Singh Boparai *et al.* (2016) |
| ABS+ elastomers, ABS+ $TIO_2$ | Perez *et al.* (2014) |
| ABS + rice straw | Osman and Atia (2018) |
| ABS + montmorillonite nanocomposites | Weng *et al.* (2016) |
| CFRP | Ning *et al.* (2016) |
| HIPS | Tanikella *et al.* (2017) |
| Ninjaflex | Tanikella *et al.* (2017) |
| Nylon-6-based nano-composite | Boparai *et al.* (2016) |
| Nylon-6 and 30-40% iron | Masood and Song (2004) |
| PEEK | Arif *et al.* (2018) |
| PLA + HA | Senatov *et al.* (2016) |
| Poly ($\varepsilon$-caprolactone) | Domingos *et al.* (2012) |
| Polyetherimide | Jiang *et al.* (2019) |
| Polyphenylene sulfone | Slonov *et al.* (2018) |
| Polypropylene + wood flour and polylactic acid + wood floor | Navarrete *et al.* (2017) |
| SemiFlex | Tanikella *et al.* (2017) |
| T-Glase | Tanikella *et al.* (2017) |
| ULTEM | Boschetto and Bottini (2014), Gebisa and Lemu (2018), Prajapati *et al.* (2018), Taylor *et al.* (2018) |

**Table II** Summary of major research in process parameters optimization of fused deposition modelling

| Researcher | Material | Process parameter | Response | Significant factor |
|---|---|---|---|---|
| Ahn *et al.* (2002) | ABS | Raster orientation, air gap, model temperature and color, bead width | Tensile and compressive strength | Air gap and raster orientation |
| Chin Ang *et al.* (2006) | ABS | Air gap, raster width, build layer and build profile, build orientation | Compressive strength, compressive modulus and porosity | Air gap and raster width |
| Anitha *et al.* (2001) | ABS | Layer thickness, speed of deposition, road width and their interaction | Surface finish | All factors |
| Arif *et al.* (2018) | PEEK | Raster angle and build orientation | Tensile strength, flexural strength and fracture toughness | All factor |
| Cao and Xie (2017) | PLA | Raster angle | Elastic constant | Raster angle |
| Chang and Huang (2011) | ABS | Contour width, contour depth, raster width, raster angle | Profile error and extruding aperture | All factor |
| Chockalingam *et al.* (2016) | ABS | Raster angle, air gap, orientation and raster width | Tensile strength and density | All factor |
| Chohan and Singh (2017) | ABS | Chemical vapour | Surface roughness, hardness and thermal behaviour | All factor |
| Dakshinamurthy and Gupta (2018) | ABS | Raster angle, slice height, raster width | Visco-elastic properties | Slice height and raster width |
| Dong *et al.* (2018) | ABS | Print speed, nozzle temperature, layer thickness, fan speed | Print quality, elastic modulus and ultimate tensile strength | Fan speed, layer thickness |
| Panda *et al.* (2009) | ABS P400 | Orientation, raster angle, raster width, layer thickness, air gap | Tensile, flexural and impact strength | All factors |
| Peng *et al.* (2014) | ABS | Extrusion velocity, filling velocity, layer thickness, line width compensation | Dimensional error, warp deformation, and build time | All factors |
| Prajapati *et al.* (2018) | ABS, ULTEM | Air gap | Thermal conductivity and inter-layer thermal resistance | All factor |
| Rajpurohit and Dave (2018b) | PLA | Raster angle, layer height and raster width | Flexural strength | Raster angle |
| Sahu *et al.* (2013) | ABS P400 | Layer thickness, orientation, raster angle, air gap and raster width | Dimensional accuracy | Part orientation |
| Ning *et al.* (2016) | CFRP | Infill speed, nozzle temperature and layer thickness | Tensile properties | All factors |
| Torres *et al.* (2016) | PLA | Infill percentage or relative density, thickness, component orientation, extrusion temperature, orientation, infill direction, speed | Tensile and flexural properties | Layer thickness and speed |
| Vishwas *et al.* (2018) | ABS, Nylon | Shell thickness, model orientation, layer thickness | Ultimate tensile strength and dimensional accuracy | Orientation angle and shell thickness |

change in prototype size. Layer height and raster width have a considerable effect on the surface finish of the part. Rao *et al.* (2012) applied chemical treatment process through using different chemicals with concentration level, exposure time and initial roughness as process parameters. Garg *et al.* (2016) explored the effect of part orientation and raster angle on surface finish, tensile strength, flexural strength, model material consumption, support material consumption and building time of ABS specimen. Samples were treated with cold vapors of dimethyl ketone, which shows improvement is surface roughness. Lalehpour and Barari (2016) studied acetone vapour bath smoothing effect on surface finish enhancement of parts made up of FDM. Process parameters were cycle duration and number of smoothing cycles. Vapour treatment breaks secondary bonds and polymer material flows in the adjacent cavities, which results in improved surface roughness (Garg *et al.*, 2016; Garg *et al.*, 2017a). Jo *et al.* (2016) addressed practical approaches to enhance surface roughness and strength of the part produced by FDM. Test conducted were shrinkage test, tightness test and tensile strength test after PPFT. Dipping method improved tightness. With the fumigation method, uneven improvement in surface roughness was found. Chohan and Singh (2017) examined the influence of six parameters (FDM process and vapour smoothing) on surface roughness of the ABS part. Results showed an improvement in surface finish, which authorized the use of these parts for investment casting of a biomedical implant. The decrease in slice thickness and bead width can improve surface finish but increases build time. Lalehpour *et al.* (2018) considered the influence of smoothing factors on the surface roughness of the final FDM part. Process parameters were a cycle duration and number of smoothing cycles. Havenga *et al.* (2018) scrutinized the influence of acetone vapor on FDM ABS parts. The study concluded as reduced tensile strength, increase in ductility and a significant reduction in surface roughness. Lead time for chemical finishing techniques was less than actual production phases; this is contradictory to the present notion that PPFTs are laborious and time-consuming processes.

Nsengimana *et al.* (2019) explored the effect of PPFTs on ABS parts manufactured through FDM. Tumbling, hand finishing, shot peening and CNC machining, spray painting and chemical treatment were the PPFT techniques that were studied. Chemical treatment technique was found to be promising in this study.

From the review of available literature, it is found that the acetone vapor bath smoothing technique is the most significant among all chemical finishing techniques.

#### 3.3.3 Laser polishing

Chai *et al.* (2018) used laser polishing as a PPFT for a FDM-manufactured part. The result showed the highest decrease, 68 per cent, in surface roughness when 3 W laser power was used. This method is an inexpensive, rapid and contactless technique to increase the surface finish of the FDM part. Results showed a 68 per cent reduction in surface roughness of the PLA part compared to 5 per cent of the ABS part. However, the surface roughness modifications of this technique on polymer parts made up of materials other than PLA and ABS should also be evaluated.

#### 3.3.4 Sterilization methods

Perez *et al.* (2012) tested nine FDM parts made from different materials for sterilization methods, namely, ethylene oxide, autoclave, gamma radiation and hydrogen peroxide. Sterilization analysis was performed by keeping samples in tryptic soy broth for some time. More deformation in ABS parts was observed in the autoclaving method, as ABS cannot resist high temperature.

On the critical review of available literature related to PPFTs, it can be concluded that mechanical finishing techniques should be further developed for achieving the desired response in case of complex geometries. Also, vapour smoothing chemical finishing technique performs better than other PPFTs but has a limitation on materials to be processed. Laser polishing technique should be further optimized and process parameters that were not studied in previous literature should be studied. Minimization of process time as a response should be included in the evaluation of present PPFTs for better comparison. Further research is required in using different chemicals for materials other than ABS. Standardization of PPFT will also improve efficiency in mass finishing. A summary of major research in PPFTs of FDM parts is given in Table III.

### 3.4 Numerical simulation of fused deposition modelling process

There is no theoretical model capable to forecast completely the complications of the FDM process; however, with several assumptions, it is possible. The strength of part manufactured by FDM can be projected by bearing in mind the strength of the fibres extruded, the bond strength among the fibres and the cavity content among the fibres. The strength of the extruded fibres is equal to that of the virgin polymer, and an analytical model has been exploited for forecasting cavity content in the parts. Therefore, merely the bond strength should be

**Table III** Summary of major research in post-production finishing techniques of fused deposition modelling

| Method | Researcher | Remarks for surface finish improvement techniques |
|---|---|---|
| **Hot air** | Adel *et al.* (2017) | Good for surface finish improvement |
| **Laser polishing** | Chai *et al.* (2018) | Cheap, fast and contactless method for surface finish improvement |
| **Vapor smoothing** | Chohan *et al.* (2017) | Best for surface finish improvement |
| **Microsandblasting and PVD** | | |
| **Acetone dipping** | Galantucci *et al.* (2009) | Good for surface finish improvement |
| **Vapor smoothing** | Garg *et al.* (2017a) | Best for surface finish improvement |
| **Vapor smoothing** | Havenga *et al.* (2018) | Best for surface finish improvement |
| **Dipping, fumigation, resin filtration** | Jo *et al.* (2016) | Resin filtration method was better among other methods |
| **Vapor smoothing** | Lalehpour and Barari (2016) | Best for surface finish improvement |
| **shot peening, tumbling, spray painting, hand finishing, CNC machining, chemical treatment** | Nsengimana *et al.* (2019) | Chemical treatment is found best for surface finish improvement |
| **Hot cutter machining** | Pandey *et al.* (2003a) | More time requirement for complex geometries, tool changes with geometry change |
| **Various sterilization techniques** | Perez *et al.* (2012) | Sterilization methods studied are autoclave, ethylene oxide, hydrogen peroxide, gamma radiation |
| **Chemical treatment** | Rao *et al.* (2012) | Good for surface finish improvement |
| **Barrel finishing** | Singh and Trivedi *et al.* (2017) | Complex, slow and local surface finish control is not possible |
| **CNC assisted selective melting** | Taufik and Jain (2016) | Easy and compatible with CNC milling |

determined to include all components for computing strength of FDM parts (Dabiri *et al.*, 2014; Coogan and Kazmer, 2017).

Prediction of properties of the final part is a complex problem involving heat transfer, solidification, fluid flow and free boundary. Therefore, a literature review of numerical simulation (finite difference method/finite element method/ finite volume method) of the FDM part and process testing is imperative.

*3.4.1 Numerical simulation of fused deposition modelling process*

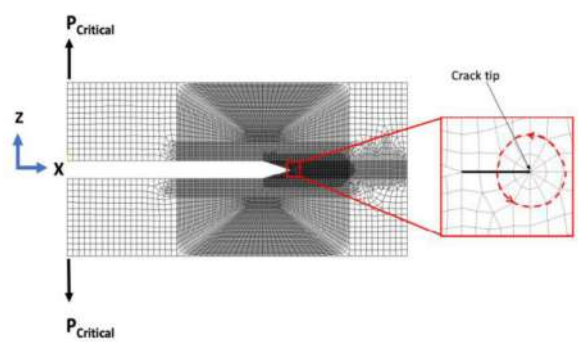
Umetani and Schmidt (2013) established a novel structural analysis procedure that detects critical stress inside 3D printed objects based on bending moment equilibrium equation. Then optimum print orientation was selected to print with maximum strength. Euler–Bernoulli assumption greatly reduced the complexity of FEA, making it available for real-time visualization of interactive tools. The isotropic material assumption was considered in this analysis. Peng *et al.* (2014) concluded that the final quality of FDM part depends upon the proper choice of operating parameters, which is a complicated problem including unsteady heat flow, a free boundary, heat transfer and solidification. They developed fully resolved numerical simulation to test polymer injection, cooling down and fusion with already build material. Han *et al.* (2017) designed and analysed FDM nozzle for color mixing. The reason for nozzle blockage is revealed by finding the nozzle's suitable temperature at different extrusion speed. Finally, experimental validation is done on the manufactured nozzle. Coogan and Kazmer (2017) presented a diffusion regulated curative model for the prediction of FDM bond strength among layers in the $z$-direction. One dimensional transient heat examination of the interlayer boundary was presented by temperature-dependent diffusion model. Total polymer diffusion was used to forecast bond strength which was matched with a gauged bond strength of printed ABS parts. Xia *et al.* (2018b) displayed a mathematical model and numerical model of the FDM process, with the help of the finite difference method. Material viscosity is considered a function of temperature, and the object was considered rigid when it cooled down. Yang and Zhang (2018) established a numerical model of temperature filed and stress filed for the FDM process by FEA method and "birth-death element technique". They presented thermal-structural non-linear transient coupled analysis. The FDM process is a complex combination of structural and thermal analysis, as it involves phase change from liquid to solid state with the release of phase transformation latent heat. Honeycomb, grid, wiggle and rectilinear were four different scanning filling patterns studied, of which honeycomb provides the most uniform stress distribution and smallest deformation. Zhang *et al.* (2018) investigated the FDM process by using a FEA element activation model to replicate mechanical and thermal phenomena involving complicated heat and mass transfer. It was observed from results that short raster length results in greater residual stress and, therefore, higher distortion. Simulations of joint thermo-mechanical phenomena were spent to analyse stress build-up during accumulation and part distortion. The study shows a distinctive aspect of FDM to other AM technologies is the continuous change of geometry and boundary conditions. In the SLS or SLA process, the part is enclosed by raw material during the process, which is not the case for FDM. A FEA model was able for residual stress simulation and part deflection approximation.

From the literature review, it can be concluded that Xia *et al.* (2018b) presented the first fully resolved simulation of the FDM process. However, it should be further improved by minimizing assumptions.

*3.4.2 Numerical simulation of testing fused deposition modelling components*

Zhang and Chou (2008) evaluated the effect of deposition factors on residual stress and part distortion. Scan speed was found the most influential process parameter followed by layer thickness by simulation. ANSYS software was used to develop simulation code and rectilinear parallelepiped geometry was chosen for the element, which has dual attributes for thermal and mechanical analysis. Distortion results of simulation show similarity with that of experimental trend qualitatively. Martínez *et al.* (2013) performed a numerical simulation of two different composite structures by using ABAQUS software with ply level method and analysed obtained results. Domingo-Espin *et al.* (2015) focused on developing a good model to simulate the FDM part and correlate FEA simulation with physical testing. They presented constitutive model, which was assumed true under linear elastic deformation that governs its mechanical behaviour. ANSYS mechanical software was used to simulate the distortion of part and contact sets were used because the load was not applied in a similar location (bending). Flexural stiffness coefficients were calculated. Results showed that within the elastic limit, the material can be modeled as isotropic, but beyond this region, it is imperative to use anisotropic material properties. Qattawi *et al.* (2017) characterized fracture resistance of ABS printed double cantilever beam. They introduced pre-crack at the layer boundary and hampered it in the crack opening direction. An FEA model of the fracture test specimen with plane strain element formulation has been developed. Fracture surface analysis was established to get fracture resistance, which was gauged close to fracture resistance of bulk ABS (4,017 J/m$^2$). It was observed that fracture resistance increases with a rise in printing temperature. They provided the FEA model of a FDM part under mechanical loads (Figure 4). The difference in densities of polymer filament and AM part was used to compute the material gap because of the layer's union in the

**Figure 4** Plane strain finite element mesh of DCB with magnified crack tip




**Source:** Aliheidari *et al.* (2017)

CAD model. A number of holes per area (HPA) were introduced as one of the parameters to match the FEA model of AM part with actual AM part. Several assumptions were considered, such as model material property same as filament material property and also uniform material property throughout layers to carry out FEA analysis.

From the literature review related to numerical simulation, it can be concluded that the evaluation of interlayer adhesion characterization in between layers of AM part is possible by numerical simulation techniques which are not possible by the previous stress–strain-based testing technique, such as tension, compression, bending. The literature reviewed showed that numerical simulations of polymer injection until fusion have been developed. Numerical models for prediction of the strength of part are also studied. Correlation studied of FEA and experiment by using an element which has thermal and mechanical attribute is available in the literature. Even 100 per cent infill pattern gives gaps and porosity when viewed under scanning electron microscope (SEM) (Xia *et al.*, 2018b). In FDM, the leading heat transmission mode is conduction and convection, and consequently, the FEA model geometric change must be encompassed. The results of the raster pattern on residual stresses and distortion shape in the components are also to be investigated.

### 3.5 Recent advances in FDM technique

#### *3.5.1 Process improvement*

Pandey *et al.* (2003b) proposed a slicing process for FDM based on instantaneous edge outline of deposited layers. Various features of adaptive slicing such as stepwise refinement, local adaptive slicing, and specifying nonuniform $R_a$ value at various locations of the part have been implemented by this procedure. Wang *et al.* (2007) built a numerical model of warp distortion of FDM according to elementary hypothesis and simplification. Process parameters were also analysed including deposition layer quantity, piling section length, the temperature of the chamber and material linear shrinkage rate. Measures were suggested for a reduction in warp deformation. The proposed numerical model can deliver a scientific tool for managing and regulating the deformation. Diegel *et al.* (2011b) developed a novel curved-layer FDM process where the building of curved plastic parts that have conductive electronic property is possible. The component was printed as a primary part of the plastic component, thereby removing the printed circuit board and wiring. Wang *et al.* (2018) showed that sole melt flow index (MFI) of plastic filament is not sufficient to confirm 3D printed part quality, as plasticizer type and crystallinity also play important role in polymer melt deposition. Also, it is found that PLA3D850 was a promising 3D printer material if poly-hydroxyl butyrate was used as a blending partner. Zhao *et al.* (2018) proposed an original printing strategy, inclined layer printing, to overcome the limitation of conventional printing strategy of support generation.

#### *3.5.2 New material development*

Masood and Song (2004) produced metal/polymer combined material for rapid tooling. Iron/nylon mixture used in this study consists of iron metal elements in P301 nylon matrix for the manufacture of suitable feedstock substance. Shaffer *et al.* (2014) introduced crosslinks among polymer chains by exposing a 3D printed copolymer mixture to ionizing radiation to reinforce a part. Triallyisocyanurate was found effective as a radiation sensitizer for PLA to enhance mechanical and thermal properties. Chaunier *et al.* (2016) assessed thermo-mechanical and rheological properties of parts made of zein, a storage protein from corn. Khatri *et al.* (2018) developed ABS-barium titanate ceramic composites as a functional dielectric material for the production of capacitors and light-weight passive antennas. Zhang *et al.* (2018) characterized the tensile properties, shear properties and fracture surface analysis of ABS, carbon nanotube-reinforced ABS and short carbon fibre-reinforced ABS. Liao *et al.* (2018) assessed the thermal and mechanical properties of carbon fibre-reinforced polyamide-12 by varying the concentration of carbon fibre in the matrix of the material. Stoof and Pickering (2018) produced composite filaments of pre-consumer recycled PP by varying content of filler material, such as harakeke, hemp fibre or recycled gypsum.

#### *3.5.3 Machine improvement*

Choi *et al.* (2011) developed a FDM machine in which the extrusion head was attached below the movable build platform so that material can be deposited on any freeform surface. The arrangement is useful in part repair, 3D conformal adhesive dispensing, integrated manufacturing, etc. Mireles *et al.* (2013) successfully printed low melting point metal alloys in a conventional FDM machine. The deposition was achieved through specific modifications to system tool-path commands. Lee *et al.* (2014) developed a mixture rapid prototyping system using economical FDM and five-axis machining. The proposed system can insert metal in the FDM part, which results in increased part stiffness. Maidin *et al.* (2017) studied strength improvement in vacuum-assisted FDM with normal FDM. The vacuum system is able to sustain heat longer for the layer to bond better throughout the deposition process. This resulted in increased part strength. They further used vacuum technology to decrease the staircase effect of part printed by FDM. A surface roughness tester and optical microscope were used for this study, which shows 9 per cent improvement from a normal print (Maidin *et al.*, 2018). Soriano-Heras *et al.* (2018b) presented a system to sense extrusion stoppage in FDM machine by detecting filament movement by an optical encoder. The presented system was low cost and also avoids mechanical wear of the extruder. With this development, it is possible to print models in two colors with only one extruder and also possible to use filament remained in the spool. Al-Ahmari *et al.* (2018) proposed an optimal part orientation system to improve part quality/accuracy in AM. Part volume and time required for printing is calculated and optimal part orientation is achieved by using geometric dimensioning and tolerancing value and minimizing production time.

#### *3.5.4 Part quality improvement*

Singh (2013) fabricated small size products that are accepted as the industry standard. This study emphasized the most excellent setting of support material quantity and build orientation for the component on the FDM machine from dimensional accurateness and financial viewpoint. Tolerance grade, surface finish and hardness were acceptable as per industry standard. Belter and Dollar (2015) found that 45 per cent increase in strength and 25 per cent increase in stiffness was possible if high strength resin was filled in hollow channels and voids of FDM part. Parts manufactured by this method can be used as load-bearing elements. They showed that the strength can be improved by using this technique as placing hollow voids within the part, casting resin material into the voids and by final part features. Pitayachaval and Masnok (2017) investigated the effect of feed rate and volume of material on nozzle wear when metal-filled PLA filament was used. After component manufacturing, nozzles were cut by the milling process and were observed under SEM. Singh *et al.* (2018) performed *in vitro* study of SS316L biomedical implants prepared by FDM, vapour smoothing and investment casting. The study included a component's corrosion behaviour and bio-compatibility. Appreciable results were observed with parts having good corrosion resistance. The density of the FDM pattern and baking time of the mould were found as significant parameters for optimizing corrosion resistance. Vasilescu *et al.* (2018) discussed the economic considerations of using 3D printing components for abrasive water jet machinery. A conventional machining component was replaced by 3D printed components and economic feasibility was compared.

From the review of available literature related to recent advances in FDM, it can be concluded that curved layer FDM process for fabrication of combined electronic components is promising in solving many problems because resulting part has desired mechanical and electronic properties. Inclined layer printing is also useful in minimizing support material. Fibre-reinforced polymer, polymer-metal and polymer-ceramic parts are used to achieve desired mechanical, thermal and rheological properties. Further research in this direction will certainly open a new area of possibilities. Strength improvement of polymer part is also achieved by combining it with a metal or a resin and also by vacuum assisted manufacturing. Efforts of extruding metal-filled PLA filament have already been made and its effect on nozzle wear is analysed. Economic feasibility of replacing a conventionally manufactured part by 3D printed part has also been checked. In recent years, FDM machines have been developed that can print more robust materials such as continuous CFRP. The fabricated components of CFRP are chemically resistant, durable and can successfully substitute traditionally manufactured metal components.

## 4. Statistical analysis

Various approaches of part quality and performance improvement for FDM are considered in this paper for review. The research work published in the past 26 years from 1994 to 2019 are taken into contemplation. It is classified into various categories including process parameter optimization, effect of environmental parameters, post-production finishing techniques, numerical simulation of FDM process, and recent advances in FDM technique. Publications referred in this review are from eminent publications such as Emerald, Elsevier, Taylor and Francis, Springer, etc. Conference publications which have substantial influence towards the scope alone are also included.

Figure 5 depicts the trend of published literature during 1994-2019. It is inferred that there is a steady increase in the number of publications after 2007-2014. After 2015, the rate of research contribution in the domain has been increased significantly.

Figure 6 shows the percentage contribution of section-specific literature in the present review. It depicts that the maximum research efforts have been made in the domain of optimization of FDM process parameters.

## 5. Scope of future research

Statistical analysis discussed in Section 4 is helpful to predict current research status related to FDM part quality and performance improvement. Based on the intense review, research gaps and roadmap for future research are identified and discussed as under.

### 5.1 Research gaps

Even though worldwide researchers are engaged in improving quality and strength of FDM parts, but still, surface finish and

**Figure 6** Percentage contribution of section specific literature

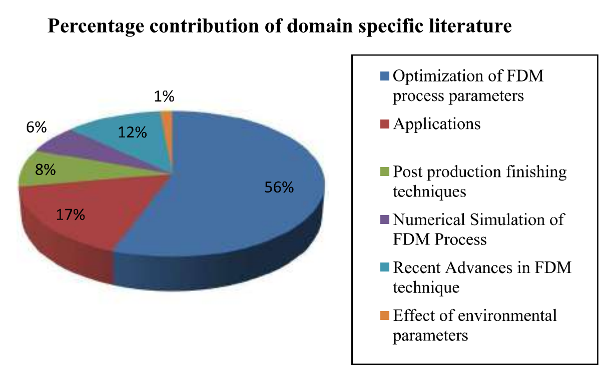
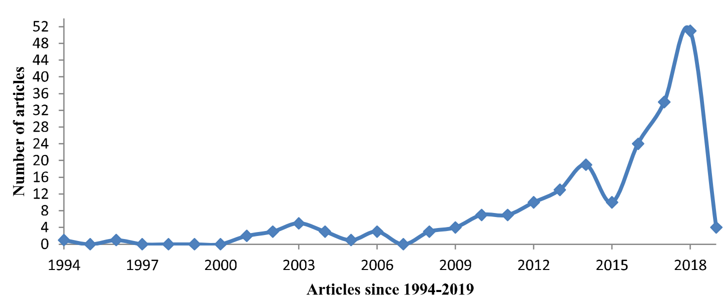



**Figure 5** Published literature during 1994-2019



strength of FDM parts are inferior to the parts manufactured by established manufacturing techniques (such as injection moulding for polymer). Therefore, there are opportunities for further research in FDM. On the basis of this detailed literature review, the scope of future research is identified in the following domains:

- There are opportunities for further research in the part production and optimization of the process for FDM feedstock materials other than ABS and PLA such as PEEK, PPSF, ASA, PS, PC-ISO, glass-filled PLA, clay, silicone, resin and an elastomer.
- Effect of the number of contours, deposition speed, base temperature and extrusion temperature on flexural strength of FDM part needs further investigation. Also, layer thickness has much significance for tensile and flexural properties, but other properties may also be affected by this parameter to a large degree. It needs further investigation.
- Most of the research on process optimization of FDM is restrained to linear and circular features. Taguchi based parameter optimization can further be extended to more complicated facets such as overhangs, gradient and curvature to have a more realistic problem.
- Fabrication of dissimilar materials (plastic and metal) in single build needs further research as both materials have a different melting point. Combining them as per functional requirement can tackle strength and stiffness duality and solve many of the current problems incurred in different applications, for example, in automotive dashboard head impact analysis.
- Fabrication of lattice structures for tissue engineering with interconnecting pores for cell growth is possible by FDM. Further research is required in investigating printing characteristic of lattice structure manufactured via dynamic process parameter of the FDM process. Also, the biomechanical performance of these structures requires further evaluation.
- Further study is required on the effect of shrinkage allowance (similar to the casting process) on the dimensional accuracy of FDM parts.
- Limited research is available in more complex analysis, such as thermal, chemical, wear, shrinkage, warpage, dynamic stiffness, hardness, creep, production time, torsion, product cost and process cost, porosity and stress and strain performance at the high-strain-rate crushing, fatigue and vibration for FDM materials. Further research needs to be done in this direction.
- Forecast nozzle wear equation and the effect of process parameters on nozzle wear should be studied.
- Limited literature is available regarding shear stress measurement of parts made by various materials. The impact test is important in measuring the service life of the component.
- Environmental factors, namely, temperature and humidity, have a damaging effect on the quality of the FDM part. Determination of optimal values of temperature and humidity for FDM manufacturing of various materials needs further study. Further, the microstructural investigation of moisture absorption is required. Temperature and humidity play an important role in moisture absorption dynamics.
- Cavities in FDM parts can be minimized by incorporating sensors in FDM machine for real-time monitoring of the process. Sensors can detect cavities and accordingly machine should be able to modify the values of process parameters and tool path.
- Currently, there is a manual intervention in entering process parameters to FDM machine that are constant throughout the build; there should be research in automatically prescription of FDM parameters on the layer-by-layer manner where each layer can have specific process parameters to maximize the benefit of AM technology.
- There is a need to explore the influence of infill pattern with lower infill percentage and analyse the effect of other factors, such as rate of cooling and environmental situations using FEA. Simulation is also needed using lamia material properties rather than isotropic material properties.
- More accurate finite element models may be developed if wetting is considered to rise continuously as a function of surface tension and temperature.
- Further study is required on the simulation of the FDM process incorporating thermal properties of materials.
- Enhancement in strength and surface finish by PVD coating on materials other than ABS should be further investigated.
- For the application of FDM parts in the medical domain, sterilization is performed. The change in tensile and impact strength of the FDM part after sterilization should be investigated.
- For framing guidelines for "design-for-manufacture (DFM)" for FDM parts, further investigation is required.
- Integration of micromachining and FDM require further research. Direct write micro-dispensing is useful to achieve resolution required for producing electrical interconnects.

### 5.2 Roadmap for future research

In recent years, researchers have become enthusiastic about development related to FDM because of the large number of possibilities. FDM has the potential of economical and safe production integrating with the overall manufacturing system. However, not only aspects such as operator, machine and feedstock material need to be considered but also environmental factors such as temperature, humidity and vacuum have a profound impact on quality of the fabricated parts.

The gaps identified in Section 5.1 need to be addressed. Table IV summarizes the gaps identified in the literature review and presents a 13-phase roadmap for addressing existing shortcomings. These phases are broadly classified into three main areas, namely, pre-fabrication (Phases 1-4), fabrication (Phases 5-11) and post-fabrication (Phases 12-13). First, the guidelines should be framed related to design for the manufacture of FDM parts as proposed in Phase 1. Then, numerical modelling relevant to FDM is proposed as given in Phases 2-3. Research related to environmental factors (optimal

**Table IV.** Roadmap for future research

| Gaps related with | Phases | Research work to be undertaken |
|---|---|---|
| **Design for manufacture** | Phase 1 | Guidelines for design for manufacture for FDM parts should be framed |
| **Numerical modelling** | Phase 2 | Simulation to be performed using layer-wise material properties (as properties of component can be varied layer wise by combined two material in same build by using dual extruder) that will aid in design of FDM parts |
| | Phase 3 | Rate of cooling and effect of environmental factors on FDM process should be numerically modelled so as to minimize approximation involved in FEA |
| **Environmental factors** | Phase 4 | Optimal value of temperature and humidity for fabrication of FDM parts made up of various feedstock materials |
| **Machine** | Phase 5 | Air cavity minimization by adaptive feedback system by using sensor that modify tool path and process parameter values |
| | Phase 6 | Automatic prescription of process parameter values by using material and loading data so as to maximize material utilization |
| | Phase 7 | Forecast nozzle wear in case of feedstock material other than polymer so as to optimize use |
| | Phase 8 | Research work related to dynamic process parameter settings (change in value of process parameter at each layer as per response requirement) |
| **Material** | Phase 9 | Fabrication of dissimilar materials in single build (e.g. polymer-metal or fibre-reinforced polymer) so as to optimize material uses in part as per desired response |
| **Process optimization** | Phase 10 | Process parameter optimization for various feedstock materials related to mechanical properties |
| | Phase 11 | Process parameter optimization for properties such as thermal, chemical, etc. |
| **Non-destructive evaluation** | Phase 12 | *In situ* process monitoring for defect-free component |
| **PPFTs** | Phase 13 | Effect of metal coating and sterilization on parts should be studied |

temperature and humidity) for the fabrication of FDM parts made up of various feedstock materials is proposed in Phase 4. Research work related to FDM machine is proposed in Phase 5-8, while that of material is proposed in Phase 9. Phases 10 and 11 provide roadmap of research work related to process optimization and PPFTs. Research work related to non-destructive evaluation is proposed in Phase 12. The last phase proposes the research work related to proper selection and optimization of PPFTs. The proposed roadmap for future research can be a vital tool for the advancement of the FDM process from just prototyping to the manufacturing of functional components.

## 6. Conclusion

Research articles published during the year 1994 to 2019 in the domain of the FDM process have been reviewed in this paper. The literature review is categorized into five sections, namely, optimization of FDM process parameters, the effect of environmental factors on FDM parts, numerical simulation, post-production finishing techniques and recent advances in FDM. More than 200 research papers have been reviewed critically, and major work is summarized in tabular form to identify the scope of future work and to propose a roadmap for future research. It is observed that substantial work has been done in the optimization of process parameters for improving the mechanical and thermal properties of FDM parts. Efforts have also been made to improve the FDM process through numerical modelling. Research has also been done in FDM feedstock. FDM process has also been successfully used in fabricating implants for medical applications.

Based on the literature review, direction for future work in FDM has been presented and roadmap for research is discussed. It is observed that much research work has been done on filament materials of ABS and PLA. However, surface finish and mechanical properties of other materials should also be investigated. Effect of environmental factors on the quality and performance of FDM parts should also be further investigated. More realistic numerical simulation of build process should be modeled and validated. Complicated loading such as creep and fatigue needs further investigation to match real-world scenario. Fabrication of dissimilar material in the same build needs further research. Further, research efforts are also needed in technology advancement, new material development and automation of the FDM process for its wide acceptability in industries. Future research in FDM could increase the build velocity of the process, refine the texture of surfaces and advance of new materials, composites, plastics and biomaterials in filament shape for required industrial products. For reducing the manufacturing time of the process, future research could involve the combination of numerous extrusion nozzles or integrating logical build approaches where the interior of the part can be filled earlier using thicker rasters and external surfaces by finer rasters.

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