Fused Deposition Modelling: Current Status, Methodology, Applications and Future Prospects

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Abstract

Fused deposition modelling (FDM) is an advanced 3D printing technique for the manufacture of plastic materials. The ease of use, prototyping accuracy and low cost makes it a widely used additive manufacturing technique. FDM creates 3D structures through the layer-by-layer melt-extrusion of a plastic filament. The production of a printed structure involves the generation of a digital design of the model by 3D design software and its execution by the printer until the complete model is reproduced. This review presents the current status of FDM, how to handle and operate FDM printers, industry standards of printing, the types of filaments that can be used, the post-processing treatments, advantages, and limitations as well as an overview of the increasing application fields of FDM technology. The application areas of FDM are endless, including biomedicine, construction, automotive, aerospace, acoustics, textiles, and occupational therapy amongst others. Even during the current Coronavirus disease (COVID-19) pandemic, FDM has helped to fabricate face masks, ventilators and respiratory systems, respiratory valves, and nasopharyngeal swabs for COVID-19 diagnosis. FDM 3D and 4D printing can produce polymeric and composite structures of various designs, and compositions in a range of materials according to the desired application. The review concludes by discussing the future prospects for FDM.

Keywords: 3D printing; fused deposition modelling; biomedical applications; tissue engineering; scaffolds

1. Introduction

Three-dimensional (3D) printing is undergoing a remarkable evolution which is leading to its exponentially growing use [1]. It was initially used to make molds or prototypes [2], however, its use expanded due to its accurate and reproducible design capabilities in a range of materials. This allowed faster fabrication of prototypes in a range of sizes, styles, materials and colours [3]. 3D printing is now accessible to the public and a basic fused deposition modelling (FDM) printer can be easily bought at a shopping mall. The FDM technology is remarkably cheaper than other additive manufacturing (AM) techniques due to its simplicity [4,5]. Today anyone can design prototypes and print them in their own home and this demand has further accelerated the advancement of multiple 3D printing techniques [6]. Of all the existing AM techniques, FDM, direct printing, injection printing, selective laser sintering and stereolithography are some of the most popular ones that are gaining significant momentum [7,8]. There are several key benefits that AM offers over traditional manufacturing including cost, speed, quality, innovation/ transformation, and impact as summarised by Attaran [9]. AM enables and facilitates production of moderate to mass quantities of products that can be customized individually and it is a powerful tool to reduce complexity in the supply chain [9]. Critical to the selection requirements for this technology is the need for appropriate materials [10]. FDM is the AM technology that exhibits the greatest limitations hindering mass production due to production times and costs [11]. Nevertheless, the capacity of FDM to enable rapid prototyping and on-demand manufacturing are key advantages the technique brings over traditional manufacturing. Furthermore, additive manufacturing techniques such as FDM are at the forefront of enabling redistributed manufacturing, which is critical in reducing the carbon footprint and enabling smart manufacturing approaches of the future.

FDM, also referred to as fused filament fabrication (FFF) was invented over 20 years ago. The acronyms FDM and FFF are both in common use within academic literature. After stereolithography, FDM is the second most commonly used 3D printing technique [12]. This technique is controlled by a rapid prototype (RP) computer, that can produce parts made of porous materials through the layer-by-layer manufacturing method [13]. FDM generally involves the generation of a digital design using a 3D design software, which is subsequently sliced into a series of laminations or layers. This layer data is communicated to the printer which reproduces the design layer-by-layer until the complete model is obtained. The mechanical properties of FDM printed parts depends on the material, the structural parameters (i.e. rasters angle, infill density, printing orientation, and stacking sequence), and manufacturing variables (i.e. printing speed, extrusion temperature and rate, layer time, nozzle transverse speed, and bed temperature) [14–17]. FDM RP has certain advantages such as control of the matrix architecture (shape, size, branching, geometry, interconnectivity, and orientation), producing a structure that can vary in design, and composition according to the material used. However, much research is being carried out to improve the printing quality control [18,19].

The increasing number of new developments and applications achieved by FDM in recent years demonstrates the great potential of this AM technology. During the COVID-19 pandemic, FDM was used as an alternative production method to produce personal protective equipment (PPE) such as face masks and respirator face shields [20–22]. A significant number of new types of materials designed for FDM have been developed between 2020 and 2021 including new fibre-reinforced composites with superior mechanical properties [23–28], advanced polymer-based nanocomposites prepared with the addition of carbon nanomaterials [29–32] and many other types of polymer-based composites [33–36] with enhanced physical properties. New ceramic-based materials made of polymer and ceramic powder such as Al_2O_3 [37], hydroxyapatite[38] or dense zirconia[39] have been developed for FDM. Regarding sustainability, new natural environmentally friendly filaments have been recently developed [40–44]. Furthermore, the addition of bioactive components to functionalize biodegradable composites for low-temperature FDM showed potent antibacterial and biocompatible properties[45].

In biomedicine, biocompatible hydroxypropyl-methylcellulose-reinforced polylactide composites [46] and new bioinspired structures have been successfully printed by FDM [38,47]. Different types of PLA scaffolds [48–50] and non-toxic and biocompatible filaments of polylactic PLA-biphasic calcium phosphates composites obtained by hot melt extrusion (HME) were also shown to be suitable for FDM of scaffolds in the field of tissue engineering [51]. 3D-printed PLA-stainless-steel polymeric composites have been fabricated for biomedical applications[52]. Multi-colour extrusion FDM has been used as a low-cost 3D printing method for anatomical prostate cancer models [53]. An acrylonitrile butadiene styrene (ABS) canine tibia model [54] and complete dentures have been fabricated by FDM [55].

In pharmacy, FDM combined with HME and optimized formulation compositions have also recently shown to be an attractive option for the development of pharmaceutical tablets and implants where adjustable drug release patterns are required [56–59]. FDM coupled with passive diffusion has shown to be an accessible loading method for filaments to allow for the manufacture of tailored personalised medicines in clinical settings [60]. Direct powder 3D printing of tablets to simplify FDM has also been recently explored [61].

The great potential of this AM technology has vastly increased its number of industrial applications. For example, an automotive brake pedal has recently been produced with metal-polymer filaments [62]. FDM has also been proposed as a viable construction technology for habitation on Mars [63] and for the fabrication of microelectrodes and multi-electrode probes [64]. Shock-resistant and affordable polypropylene (PP) dipping chambers suitable for synthesis or analytical purposes [65] and PLA dielectric substrates for microstrip patch antenna [66] have also been fabricated by FDM.

Many innovative FDM approaches have also been reported very recently such as, the manufacture of hierarchical porous polyetherimide (PEI) parts via an in-situ foaming FDM technology [67] and the manufacturing route combining FDM and laser writing for the manufacturing of multifunctional polyamide/carbon fibre composites [68].

It is also important to mention the combination of 3D printing and smart materials, which is called four-dimensional (4D) printing and it is gaining much importance in FDM manufacturing as a pioneer field to produce functional smart devices [69]. Therefore, 4D printing using FDM is an emerging innovation in AM that encompasses active materials in the printing process to fabricate a 3D object that can perform an active function [70]**.** This FDM-based 4D printing technology has opened new application fields such as thermally activated hinges [71], 3D-printed orthoses [72], high-performance and shape memory thermosets [73] and biomedical and tissue engineering technologies [74].

This review highlights the current status, the concepts of handling and operation, the industry standards of printing, the types of filaments used, the post-processing methods, the advantages and limitations, the broad range of applications and the future prospects of FDM.

2. Basic concepts of Fused Deposition Modelling

2.1. Main stages

As a general scheme, the core principle of the FDM production method is simply to melt the raw material and facilitate the creation of new shapes. The material is made of a filament coil on a wheel that is driven into a temperature-controlled nozzle which heats it to a semiliquid. The nozzle accurately extrudes and guides the molten material to build a structural element layer by layer. This replicates the outlines of a layer that has been introduced into the FDM working system by the application program. FDM begins with the virtual design of the part to be printed which is generated using a computer-aided design (CAD) software in a ".stl" format. Some of the most popular software packages used to produce this type of files are AutoCAD, FreeCAD, Autodesk Inventor, SolidWorks or Tinkercad. The ".stl" file is processed by a slicing or laminating program which converts the design into printer-specific instructions so that the printer can "understand" the design. The ".stl" file is transformed into a ".gcode" file. The specifications necessary to be able to print the part, such as print speed, size of the print thread, temperature and layer height are selected in a slicer or slicing program such as Slic3r and Cura. These programs produce a file with ".gcode" format, which can be directly read by the printer to print the design [75]. The G-code is the most broadly used computer numerical control (CNC) programming language that is used in computer-aided manufacturing to control automated machine tools including 3D printers [76]. Figure 1 shows a general summary of the FDM process.

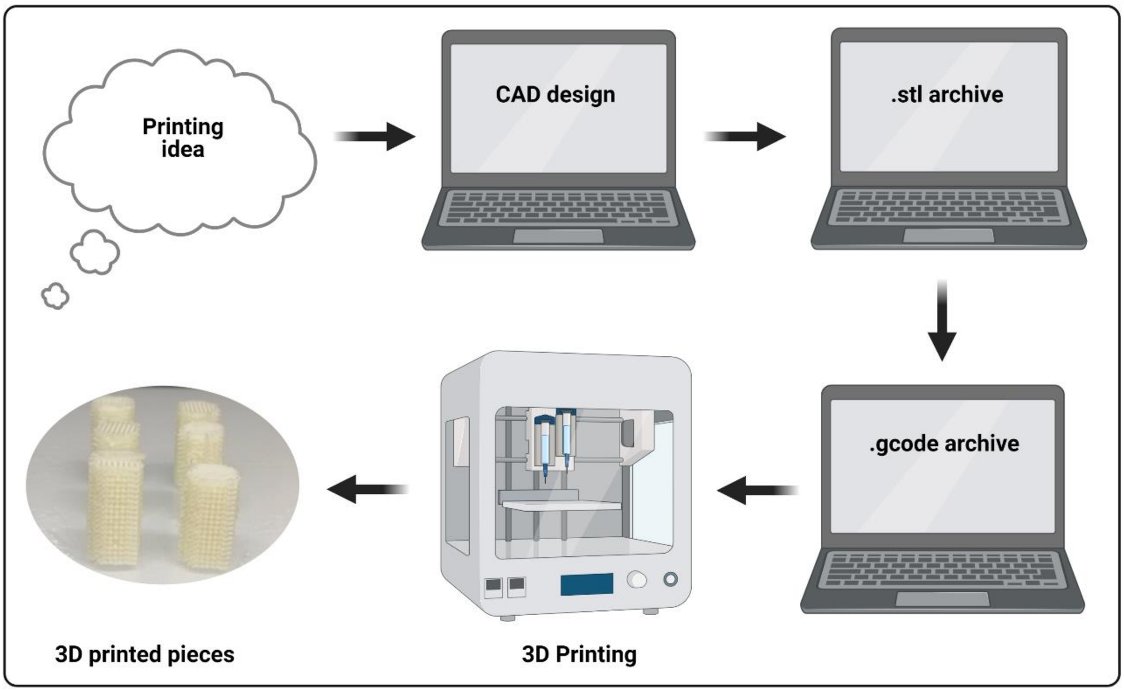

Figure 1. General summary of the FDM process

The ISO/ASTM 52901:2017 standard defines the general principles, specifies requirements and gives guidelines and applicability for use as a basis to obtain parts made of additive manufacturing, including FDM [77].

2.2. Operation

The FDM technique consists of layer-by-layer deposition of molten polymeric material, one on top of the other, until the designed part is complete (Figure 2). It consists of a polymeric filament, which is delivered from a coil and melts as it passes through the extruder, where it reaches its melting point [78]. There are two main types of 3D printers according to the movement that the extruder and print bed follow. Thus, most printers have an extruder that moves along the x and y axes to shape each layer, while the bed moves along the z-axis, descending one level each time a new layer is formed [79]. However, other 3D printers have an extrusion head that moves along the x, y and z axes to print the design [80].

The extruder is where the filament is heated to reach its melting point and thus form the designed part, also known as the extrusion process. This part of the 3D printer consists of a series of components, such as the extrusion motor, responsible for providing the power to move the filament and melt it to deposit the layers onto the print bed. The 3D printer has a pulley and a lever, which move the filament to the tip of the extruder (or hot end). The system also has a fan to cool the extruder and usually includes a Bowden tube at the extruder inlet that prevents the filament from breaking. The hot-end is at the outlet and is in charge of melting the polymeric material for extrusion [81]. The extruder is on a carriage that allows it to move in the x and y directions. In this way, as the part is being generated, the extruder moves to shape the design. Note that some printers have two or three extruders that allow them to print with multiple filaments at the same time [81].

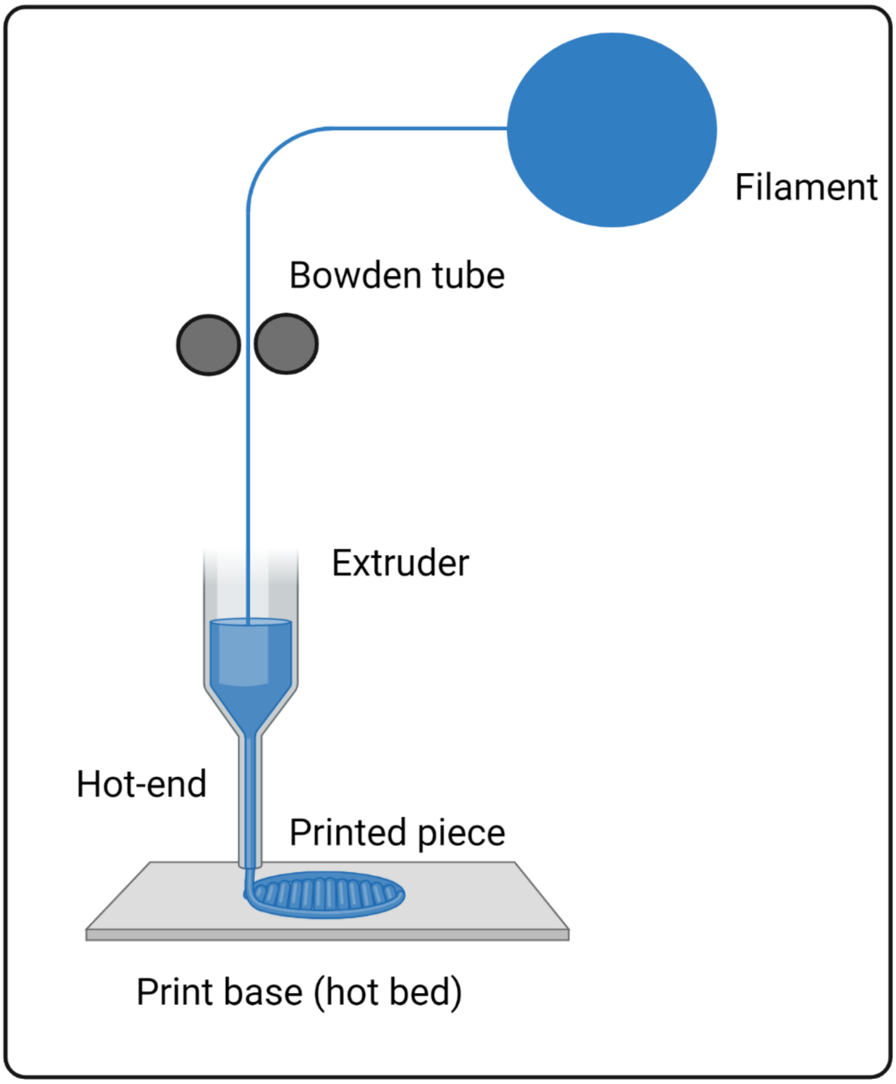

Figure 2. Basic schematic diagram of the operation of a 3D printer by FDM.

The other key component is the print base or bed, which consists of a thick material (usually glass) that serves as the substrate or the base plate for printing. There are two types of printer bases: cold or hot. A cold base is a printer base composed of a platform without heating where the extruder prints the 3D piece. However, hot bases, also called hot beds, are platforms with a heating system capable of heating the printer base to a certain temperature so that the temperature difference between the hot end and the print bed is reduced when the molten material falls on it. In this way, imperfections such as breaks in the printed part due to the change in temperature or warping that occurs when the first layer of a part deforms and detaches from the printing bed, can be avoided. [82]. Warping is common especially in large pieces because there are greater thermal differences leading to residual stresses that cause the printed part to peel off at the corners.

2.3. Industry standards of printing

There are two main types of extruder setups found on FDM printers: the direct and the Bowden extruders [83]. The moving print assembly is composed of the hot-end and the nozzle in the direct extruder, and a motor pulls the filament off the spool and drives it directly into the hot-end. The Bowden extruder has a motor that pushes the filament from the spool through a tube connected to the hot-end and nozzle. The Bowden setup presents the advantage of significantly reducing the weight of the moving print assembly, which enables a faster and more enhanced move [84].

FDM nozzles are made of metals such as brass (copper-zinc) alloy or stainless steel due to their relatively high thermal conductivity and tight fabrication tolerances [85,86]. Another nozzle characteristic is the inner diameter that generally ranges from 0.18 mm to 1.07 mm [87].

Several tests can be performed to characterize the mechanical properties of FDM materials such as tensile test (ASTM D638), flexural test (ISO 178) and short-beam shear test (ASTM D2344M)[88], and there are many studies that demonstrate that changes in the printing parameters cause differences in the characteristics of the final 3D piece [89–95]. Thus, multi-factor coupling such as different printing temperatures, printing directions, printing paths, and layer thicknesses have been shown to influence the tensile strength, bending strength, crystallinity, and grain size of FDM printed parts [96]. The mechanical properties of the 3D printed pieces are limited by the weak interlamination bonding as well as the poor performance of raw filaments used [89]. Thus, temperature control can increase inter-layer bonding strength in FDM [97]. Printing parameters such as nozzle diameter, layer height, raster angle, and nozzle temperature have been shown to affect composite samples' tensile strength, density, and production time [90]. FDM process parameters such as layer thickness, extruder temperature, filling structure, and occupancy rate can affect the mechanical properties in terms of tensile strength, elongation, and impact strength of 3D printed pieces [91]. Other important parameters to take into account are the infill and nozzle diameter [98]. These parameters affect the pore size and porosity of the FDM printed parts. Infill density has shown a considerable influence on the tensile strength and surface roughness of FDM printed parts [99,100]. Additionally, the size of the nozzle allows the extrusion of different thicknesses of materials [101]. The temperature and building orientation of the nozzle influences the relative density, flexural strength, tensile strength, breaking elongation and impact strength of the polymers [102]. Moreover, the layer thickness affects irreversible thermal strain and mechanical properties [103]. Recycling of FDM waste, which is nowadays fundamental in a circular economy perspective, can also change the mechanical properties of the pristine material [104]. FDM feedstock exists in the form of filament with an average diameter of 1.78 mm, although diameters as large as 3 mm can still be found [105]. The average diameter and its variance are important parameters that affect the extrusion process [106].

2.4. Types of filament materials for FDM

Some examples of the types of filament materials used in a FDM printer include PLA, PVA, ABS, thermoplastic elastomer (TPE), polycarbonate (PC) and PLA with graphene (Figure 3).

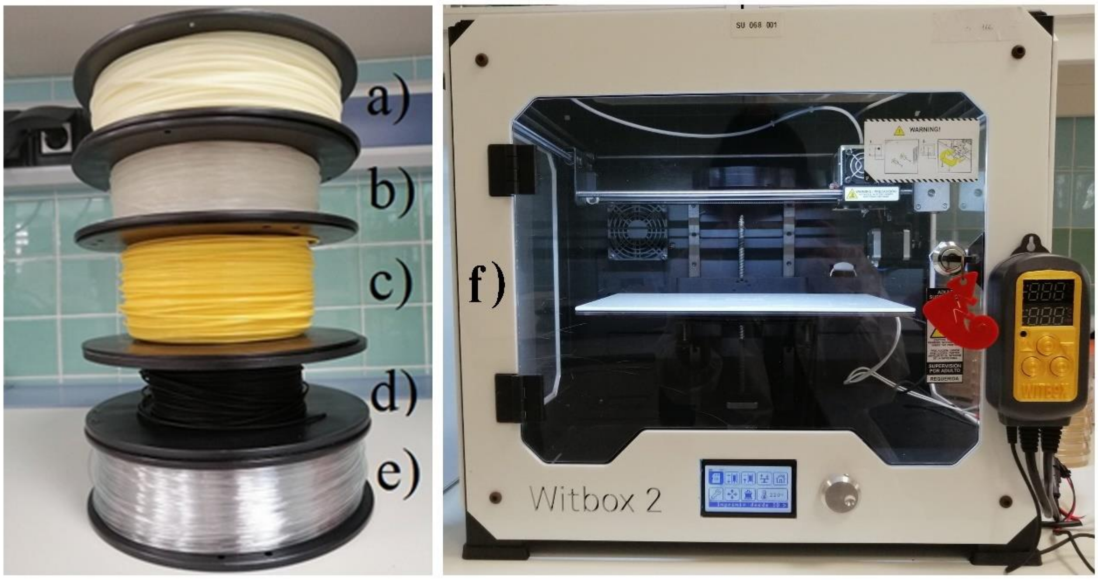

Figure 3. Example of types of filament materials available: a) Polyvinyl alcohol (PVA); b) Thermoplastic elastomer; c) Polylactic acid (PLA); d) Polylactic acid with graphene (PLA/graphene); e) Polycarbonate (PC), used in 3D printer BQ Witbox 2 with a bed heater (f).

However, there are many different types of filaments for the same material depending on each manufacturers specification, and thus they can have different melt/processing temperatures due to various properties in terms of mechanics and processing [8]. Furthermore, polymer filaments may be filled with metal nanoparticle reinforcement to prepare nanocomposite filaments to improve different features such as thermal resistance and mechanical performance [107].

In order to understand how a 3D piece can be printed from a roll of polymer-based filament, it is necessary to understand the thermal behaviour of the polymer-based filament when the temperature reaches the glass transition temperature (T_g) or the melting temperature (T_m). Thus, T_g is the temperature at which the polymer transition from a crystalline to a rubbery state occurs [108], while T_m is the temperature at which the polymer transition from a solid to a fluid state occurs [109]. When the temperature of the FDM extruder reaches the T_m, the polymer-based material can be printed.

2.4.1. Polylactic acid

PLA is a biodegradable plastic made by fermentation of crops such as corn or potatoes [110,111]. It is printed at a temperature between 160-230ºC and does not need a heated bed. It is non-toxic, low-cost, hard and strong, but brittle at the same time [112]. Due to its biodegradability, easy processability and excellent physical and biological properties, its applications are endless, including advanced applications such as tissue engineering [113], and in biosensors [114].

2.4.2. Acrylonitrile Butadiene Styrene

ABS was one of the first materials to be developed for 3D printing. It is resistant to wear, impact, withstands high temperatures and has a low cost [110]. Its great disadvantage is that it melts at temperatures between 215-250ºC and so needs a hot bed to avoid warping, and it is also made from oil. As with PLA, it has many applications such as the manufacture of microdevices [115] and microfluidics [116]. Acrylonitrile styrene acrylate (ASA) is an ABS derivative printed in conditions similar to ABS (temperature between 235-255ºC) and requires a heated bed between 90-120ºC [117]. Its main advantage is that it is UV-resistant and so can be used in exterior applications [118].

2.4.3. Polyvinyl alcohol

PVA is a water-soluble material, i.e., it dissolves in contact with water. It is printed at similar temperatures to PLA (160-230ºC) and is usually used as a support material to be easily dissolved later [110]. Other applications of this polymer include its use for dental models [119] and its wide use in the cross-linked state in biomedical applications as a hydrogel in bioprinting, i.e. 3D printing of a biomaterial combined with cells for regenerative medicine [120,121].

2.4.4. Thermoplastic elastomer

TPE is a flexible material that deforms easily so that it can counteract any type of load. It is printed at 180-230ºC and does not need a hot bed [122]. Due to its great flexibility, the filament must be fed directly to the extruder without going through the Bowden tube [36]. Its characteristics have revolutionized the textile industry for printing of clothes [123]. It is also used to make TPE orthotic insoles [124].

2.4.5. Polycarbonate

PC is a transparent material resistant to very high temperatures, slightly flexible and highly resistant to impacts [125–128]. Its biggest drawback is that it must be printed at 200-280ºC, so it needs a very high-temperature hot bed between 80-100ºC [129]. Despite this disadvantage, it is widely used due to its excellent biomedical properties for orthopaedic, dental applications [130] and tissue engineering [131].

2.4.6. Polylactic acid with Graphene

Graphene is one of the latest materials to be used in 3D printing [79]. As it is usually mixed in a low concentration with PLA, it is printed at temperatures similar to PLA of 210-230ºC. However, it needs a heated bed due to its thermal properties. The main characteristic of graphene is its excellent biological and physical properties such as mechanical, thermal and electrical conductivity, which provides conductive filaments [132–135]. This material can be used for electrical stimulation to enhance cell proliferation, or achieve cell differentiation on porous 3D printed supports for tissue engineering applications [136]. These filaments are more resistant than those of ABS or PLA [120,137]. Its applications include surgical tools [138], 3D bioprinting [121], and electromagnetic induction shielding [139].

2.4.7. Polyethylene terephthalate glycol

PETG is based on polyethylene terephthalate (PET) modified with glycol. PETG is printed at about 220-250ºC, and needs a hot bed at 60ºC [140]. Its properties are notable tensile toughness, transparency, flexibility, high processability and excellent chemical resistance [141]. One of its drawbacks is high porosity in the printed product [142], but this can also be an advantage in specific applications such as bone models [143], custom-made laboratory hardware [144] and orthopaedics [145].

2.4.8. Polyetheretherketone polymer

PEEK is an organic thermoplastic polymer with excellent mechanical properties, good lubricity, and chemical resistance. It is more flexible than ABS or PLA [146]. However, its main disadvantage is the high printing temperatures requirement of over 340-440ºC, which very few 3D printers are capable of [147]. PEEK is used in aircraft parts, rockets, racing cars and drones, and in medicine for orthopaedic implants, joint replacements, spinal implants, prosthetic systems, and dentistry [2].

2.4.9. Nylon fibre reinforced with aluminium oxide

Nylon fibre reinforced with aluminium oxide is a new type of filament with good properties like tensile strength, elasticity [148] and high-thermal stability [149]. Nevertheless, it is printed at 230-250ºC and needs a high temperature hot bed [150]. This filament is mainly used in aerospace and automotive engineering applications [2].

2.4.10. Polylactic acid with wood

One of the advantages of PLA reinforced with wood is the reduction of petroleum-based plastic and its environmental impact [151]. Its tensile strength is similar to PLA or ABS [152]. Like PLA, it is printed at 210-230ºC, and is mainly used to make ornaments [153].

2.4.11. Polyhydroxy-alkanoates

Polyhydroxy-alkanoates (PHA) is a thermoplastic polyester [154]. Its printing temperature is 110-170ºC and it has low thermal stability [155]. It can be produced by the fermentation of numerous bacteria and extremophilic archaea, making it a good candidate for use in medicine [42,156,157]. However, as its production is very expensive it is not commercially available at present and not viable for any industrial applications other than biomedicine.

2.4.12. Polyethylene terephthalate

PET is made from petroleum and its printing temperature is 210-230ºC. PET is similar to ABS because it is flexible, strong, biodegradable, and low-cost. However, it absorbs moisture [118]. PET is a biocompatible material suitable for manufacturing biomedical scaffolds [158].

2.4.13. High impact polystyrene

High impact polystyrene (HIPS) has high impact resistance [118] and is predominantly used in prototypes [159]. It is printed at 210-240º and needs a hot bed at 80-115ºC [160]. Since its printing conditions are similar to ABS and it is soluble in limonene, it is used as a soluble support material for ABS structures in biomedicine [161].

2.4.14. Cellulose materials

There is now a growing interest in cellulose materials for 3D printing because they are easily available, have great flexibility, and are low-cost and biodegradable [162]. These materials are used for a wide variety of applications such as decorative elements and in medical, electronic or textile applications. [163].

The most important properties and applications of 3D printing filaments are summarized in Table 1.

Table 1. Key properties and applications of 3D printing filaments: material, extruder temperature (T_E), bed temperature (T_B), glass transition temperature (T_g), advantages, disadvantages and applications.

MATERIAL	T_E (°C)	T_B (°C)	T_G (°C)	ADVANTAGES	DISADVANTAGES	APPLICATIONS
PLA	160-230[110,112]	20-60[110,158]	60-65[164]	Biodegradable [110], non-toxic, low cost[112]	Tough, strong [112]	Tissue engineering[113], biosensors [114] acoustics[165]
ABS	215-250 [110]	80-110[110,158]	104-109[166]	Heat resistant, strong, durable [110]	Needs high temperature and hot bed, toxic[110]	Microdevices [115], biomedicine [116]
PVA	160-230 [110,112]	20- 45[110]	45-69[167,168]	Water-soluble, useful as a support [110]	Affected by humidity [110]	Bracket, dental models [119]
TPE	180-230[110]	20-55[110]	≈ -35[169]	Flexible[110]	Low temperature stability[170]	Textile [123], orthopaedic insoles [124]
PC	200-280[125,126]	80-100[129,158]	140-150[125,126]	Resistant to shocks and high temperatures[127,128]	Needs high temperature and hot bed [125,126]	Dental[130], orthopaedic [171],tissue engineering[131]
PLA/GRAPHENE	210-230[138]	≈60[138]	≈70[138]	Conductive, resistant [137]	Needs hot bed, difficult to print	Surgical tools [138], bioelectronics [172], electromagnetic induction shielding [139]
PETG	220-250 [140]	≈60[140]	≈74[173]	Notable tensile toughness, transparency, flexibility, high processability, and excellent chemical resistance [141]	The final product has high porosity [142]	Bone models [143], laboratory hardware [144] and orthopaedics [145]
PEEK	340-440[147]	110-150[174,175]	≈143[147]	Excellent mechanical properties, good lubricity, and chemical resistance. Flexibility [146]	Needs very high temperature and hot bed [147]	Engineering industry orthopaedic implants, joint replacements, spinal implants, prostheses and dentistry [2]
NYLON WITH ALUMINIUM OXIDE	230-250 [150]	≈55[150]	60-78[176]	Good mechanical properties [148] and high thermal stability [149]	Needs high temperature and hot bed [150]	Aerospace and automotive engineering applications [2]
PLA WITH WOOD	210-230 [153]	20-55[110]	65-66[152]	Reduced environmental [151] impact and good tensile strength [152]	Wood particle clustering and clogging in the printer nozzle[152]	Ornaments [153]
PHA	110-170[156,177]	20-60[177,178]	(-1)-(-30)[156,179]	Produced by fermentation of numerous bacteria and extremophilic archaea [177]	Expensive, not on market, low thermal stability [177]	Tissue Engineering and other biomedical applications [155,180,181]
PET	210-230 [118,158]	≈75[158]	67-81[182]	Flexible, strong, biodegradable and low-cost [118]	Absorbs moisture [118]	Scaffolds [158]
HIPS	210-240 [160,183]	80-115[160,183]	80-120[160]	High impact resistance [118], soluble in limonene [161]	Need high temperature and hot bed [160]	Prototypes [159], support [161]
CELLULOSE MATERIALS	120-210[163,184]	≈70[184]	37-42[184]	High availability, low cost, great flexibility and biodegradable [162]	Little studied	Decorative elements, medical, electronic or textile applications. [163]

It is important to mention the relevant aspects that affect the printability of each of these materials. Thus, the presence of additives or fillers, as well as chemical and structural changes produced by printing have the potential to significantly impact printability and other relevant characteristics such as surface reactivity, functionalization, and association with atmospheric contaminants, organic species, cells and organisms

[79,151,164]. Additives such as chain extenders and impact modifiers have been proposed to improve printability of renewable resource-based engineering plastics tailored for FDM applications [185]. Polymer blends have also been investigated to improve the printability in FDM [126,186]. Experimental results have evidenced how material modifications have a strong impact on rheological behaviour, which has a key role in printability [126,187]. Thus, the printability of non-commonly used 3D printing filament materials such as PP can be improved by talc filling [187]. Printability and thus the quality of 3D printed pieces can change according to the PLA colour used [188]. Cuiffo *et al.* have shown that the FDM printing process results in chemical and structural changes in PLA [164]. Several materials with excellent mechanical properties such as ABS, PC, PEEK and HIPS need high printing temperatures and a hot bed [110,147,160]. Therefore, it is important to be aware of potential issues related to material transformations during printing, as well as the somewhat uncertain nature of commercial filaments [164].

2.5. Post-processing of FDM printed parts

Research has been carried out to identify the factors affecting print quality and measures to reduce surface roughness by post-processing as an additional step to reach the finish required [189]. Thus, many post-processing methods to improve surface roughness in FDM parts have been investigated and applied, and can be categorized into two types – chemical and mechanical processes [190]. Chemical post-processing procedures consist of paintings, coatings, heating and/or vapor deposition [190–193]. Thus, for example, novel post-processing techniques of FDM pieces to improve surface roughness and reduce heat absorption for high-temperature applications were developed by chemical treatment, drying and aluminium coating [194]. Other authors have proposed several economic and rapid strategies of chemical treatments with acetone-based solvents to modify printed ABS pieces to significantly improve their surface finish with minimal variations in dimensional accuracy [195,196]. Surface treatments with dichloromethane have been proposed to eliminate printing lines on polycarbonate components fabricated by FDM [197]. However, it is of note that the application of chemical post-processing methods to improve the surface finish of printed pieces obtained by FDM can modify their degradation and thermal properties [191]. Mechanical post-processing methods mainly include machining [198], abrasives [199], barrel finishing [200], sanding [201] and vibratory processes [190]. A novel post-processing tool, namely thermally assisted finishing tool (TAFT) has been designed and developed for thermally assisted finishing (TAF) of FDM built parts on CNC milling machines to improve their surface finish conditions [202]. The surface quality of FDM parts has also been enhanced by subjecting them to acetone chemical vapour smoothing (CVS), shot-blasting and laser-assisted finishing post-processing methods [189]. Improvements in surface roughness and dimensional accuracy of biomedical implants have been achieved by combining FDM, CVP and investment casting, which is a renowned process for producing dimensionally accurate and highly finished casts [203]. Partial dentures have been prepared with a synergistic combination of FDM assisted CVS patterns and conventional dental casting [204]. Very recently, laser polishing was shown to improve the surface quality, mechanical and thermal properties of FDM aluminium/PLA composites [205]. These examples highlight the potential of post-processing techniques to improve one of the most important limitations of FDM, the poor surface quality or characteristic texture.

2.6. Limitations of FDM

Although FDM was developed more than 20 years ago and its great advantages have been studied in this review, this technology still has several limitations. The primary disadvantage of FMD is that it is currently limited to processing polymer-based materials [206]. Another handicap is the low printing speed of FDM that results in a low rate of production of the print samples in comparison with other AM techniques [207]. The imperfections in the final 3D pieces such as defects and anisotropy, rough surface finish, variations in the dimensions of printed parts, and dependence on processes used are other notable challenges using FDM [208]. Similar to other AM techniques, the material properties of 3D printing parts using FDM depend on printing conditions (e.g., speed, power, temperature, process). The accuracy of FDM prints depends on different factors such as the nozzle diameter, the filament material properties and the processing parameters used [209–211]. As such the accuracy of the 3D printed parts is affected by the processing parameters during the printing process because they can affect shrinkage, bonding and warping during cooling, which subsequently affects part assemblies [212–216]. The requirement for significant post-processing to bring the printed parts to the desired surface quality is another aspect that need consideration while using FDM. This is due to the fixed nozzle and feed diameter resulting in the layer-by-layer patterns of a predetermined thickness that can obscure fine features in the part depending on their dimension. Lastly, in comparison to other techniques such as stereolithography (SLA), digital light processing (DLP) and selective laser melting (SLM), FDM is not yet suitable to be adopted for large mass market fabrication primarily due to their inconsistency in part and material quality. Therefore, FDM is more suitable for small to medium scale production of complex non-safety critical components.

3. Applications

The rapid development of FDM due to its great advantages, such as the low material cost, has greatly increased its possible applications (see Table 2).

Table 2. Immense application areas of fused deposition modelling and its specific uses.

AREA	SPECIFIC USE	*REFERENCE*
BIOMEDICINE	Prosthesis, insoles, and implants	[2,124,145,217,218]
	Tissue engineering	[113,131,155,158,219,220]
	Bone models	[143]
	Biosensors	[114]
	3D bioprinting	[120,121]
	Bioelectronics	[139]
	Complex bioengineered organoids and laboratory models	[221–225]
	Surgical tools	[138,226,227]
	Laboratory hardware	[144]
	Drug delivery system and personalized medicine	[228–236]
	Dentistry	[2,119,130,218]
ENGINEERING & ARCHITECHTURE	Microdevices	[115]
	Microfluidics	[116]
	Electromagnetic induction shielding	[139]
	Automotive industry: 3D printed molds, racing cars and parts of Formula 1 cars	[2,210,237]
	Aircraft, drone parts and rockets	[2,238]
	Personal protective equipment: face masks and respirator face shield	[20–22]
	Acoustics	[165,239–241]
	Houses and spatial meshes	[242,243]

TEXTILE INDUSTRY AND OTHER FIELDS	Fabrics	[123]
	Occupational therapy: aids for dependent people	[244]
	Support to other filaments	[161]
	Ornaments	[153]
	Prototypes	[159]

3.1. Biomedicine

FDM using filaments made of biocompatible polymers often show good mechanical performance and structural integrity making them suitable for broad a range of biomedical applications [230]. As such FDM has enabled numerous advances in medicine, especially in personalized medicine, where it has made possible customized treatments, prostheses, insoles and implants [2,124,145,217,218]. FDM is also ideal for manufacturing scaffolds that can act as an artificial extracellular matrix (ECM) in tissue engineering applications (Figure 4).

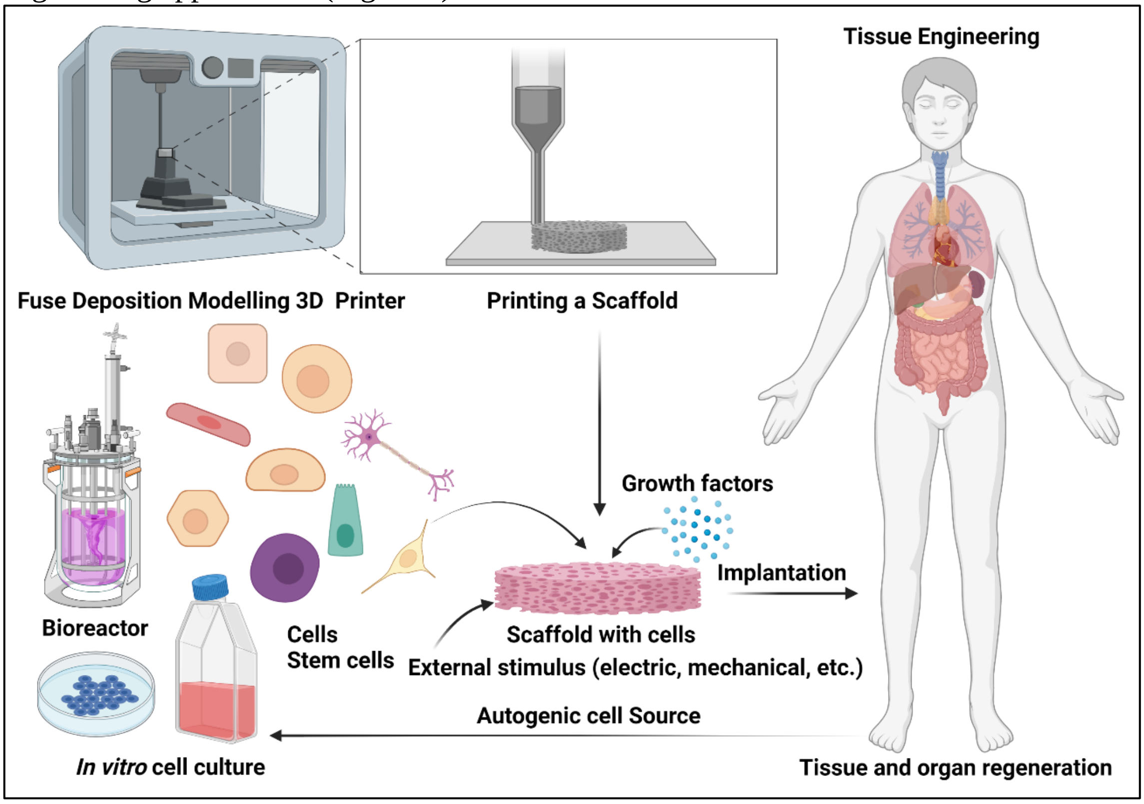

Figure 4. Printing a scaffold using a FDM printer for tissue engineering applications.

FDM offers advantages by allowing precise control of scaffold architecture with respect to shape, size, branching, geometry, interconnectivity, and orientation, making it highly suitable for tissue engineering. The role of biomaterials here is to provide a 3D cell support that controls and guides localized tissue regeneration and provides potentially controllable cellular microenvironments similar to those *in vivo* [230,245]. Scaffolds are used as supports for the tissue growth of bone, cartilage, ligaments, skin, blood vessels, nerves and muscle [246]. Biodegradable scaffolds can be utilized to bioengineer entire organs by allowing the material to disintegrate as new tissue is generated [247]. Traditional scaffold fabrication methods do not have the ability to incorporate internal architecture and control scaffold porosity [248–251]. However, FDM can provide a higher reproducible control of the size and distribution of pores required for tissue engineering applications [219,252–254].

Most biomaterials used in 3D printing can be used for the fabrication of bone models [143]. Biosensors [114], laboratory hardware [144] and highly complex bioengineered organoids and laboratory models [221] can be produced by FDM. Many laboratories have created biologically functional models composed of a wide variety of tissues such as neurons [222], kidney [223], skeletal muscle [224], liver [225], etc. In these cases, the technology used was bioprinting, which deals with polymer gels where no melting of polymers occurs. This promising emerging technology is capable of deposition of cells and biochemical components layer by layer to create defined structures using materials, bioactive molecules and cells [255]. It should be mentioned that although most surgical tools serve a wide variety of patients, some operations may require the use of unique instruments [226]. The ability to manufacture effective surgical tools by this means also favours underdeveloped countries since it can reduce costs by more than 90% [256].

Most 3D printed biomaterials can be used for drug release of molecules such as antibiotics, growth factors, biometals, etc. [228,229,257]. The development of novel drug delivery systems and personalized medicine can be achieved effortlessly if the production technology has ease of adaptability based on the patient's needs. FDM technology in which a carrier filament can be fabricated using polymers loaded with an active pharmaceutical ingredient (API), can be used to 3D print personalised tablets with modified release profiles [258] (Figure 5).

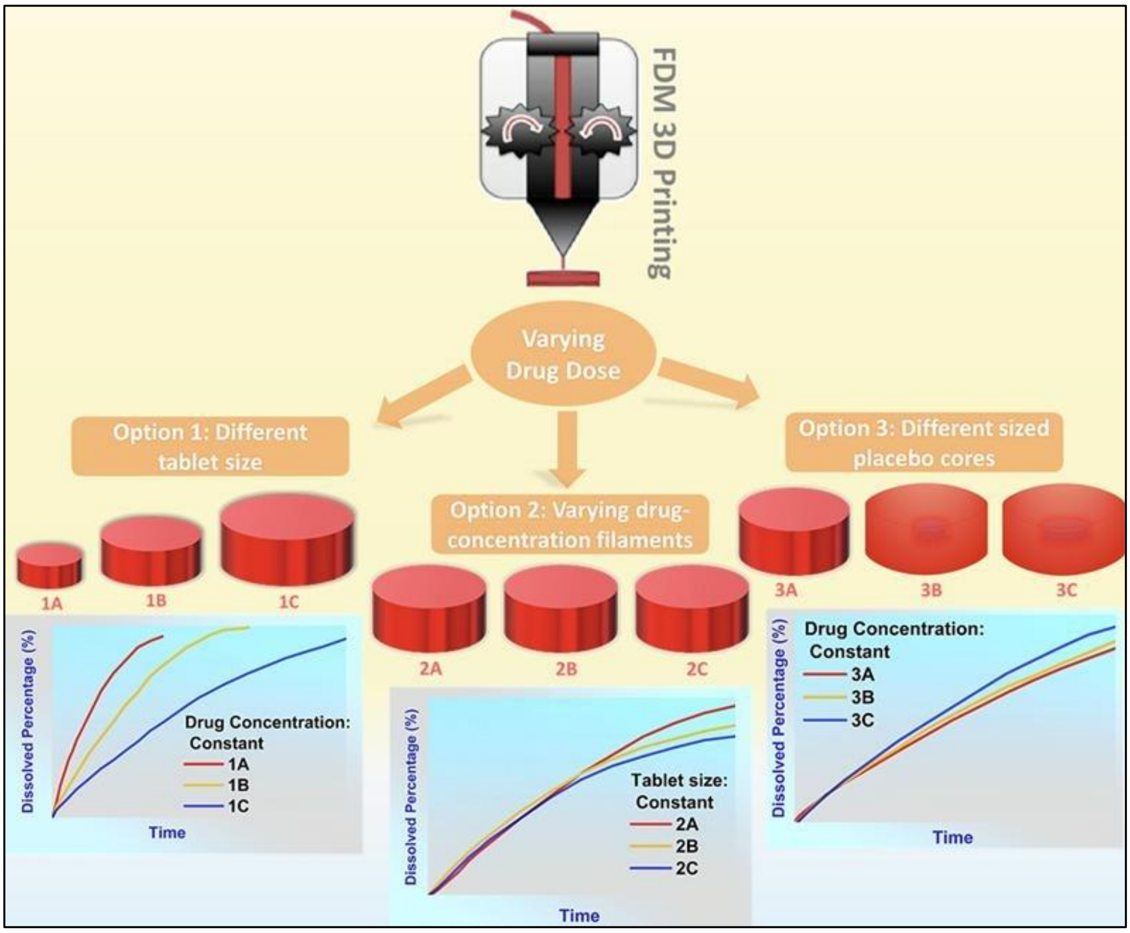

Figure 5. Tablet design options for tailoring drug release and dose via fused deposition modelling. Reprinted with permission from Ref.[259].

Thus, FDM is one of the popular AM techniques in the development of pharmaceutical tablets, owing to its low printer cost, good print quality and ability to use filaments loaded with APIs [231]. For tablet printing, the API containing filaments can be either prepared via extrusion or by soaking the polymer filaments in solution containing the API [232]. Another technique is to soak the 3D-printed tablet in a solution containing the API [233]. However, soaking techniques require an additional drying phase which prolongs the overall tablet production process. Also, the filament soaking method allows very low amounts of API to be incorporated in the tablet and improved uniformity of the dose.

It has been reported that HME, which is the process of pumping raw materials with a rotating screw under elevated temperature through a die into a product of uniform shape [260], allows for the fabrication of filaments with uniform quantity of API and good mechanical properties [261–263]. The key advantage of HME is the incorporation of higher drug quantity and control of dosage since once the drug-loaded filaments are extruded, they can be used in FDM printers to produce tablets with the desired dose and with different shapes and drug release profiles [234–236]. In summary, FDM combined with HME can lead to the fabrication of oral tablets with customized dosage and desired release profiles. Moreover, FDM is a relatively easy process and does not require extensive post-processing. The major limitation of FDM however is the use of high temperatures which limits the use of thermolabile APIs as these drugs will be degraded during filament production. Therefore, there is a need to develop polymers with low melting points for the FDM processing of temperature sensitive drugs.

Other biomedical applications of FDM include the fabrication of dental models in dentistry and dental applications such as denture flasks, bites, mouth guards and oral drug delivery devices [2,107,119,218]. PEEK has been proposed widely in oral and cranio-maxillofacial surgery, which renders possible its use for the fabrication of dental implants [218]. The technology of FDM has allowed the fabrication of medical modelling in dentistry [264]. Thus, the first patient treated with the help of FDM occurred in 1999 using a 3D printed medical model of the complex anatomy of the patient's cleft palate. FDM technology has also been used in dentistry to produce dental crowns (Figure 6) [107].

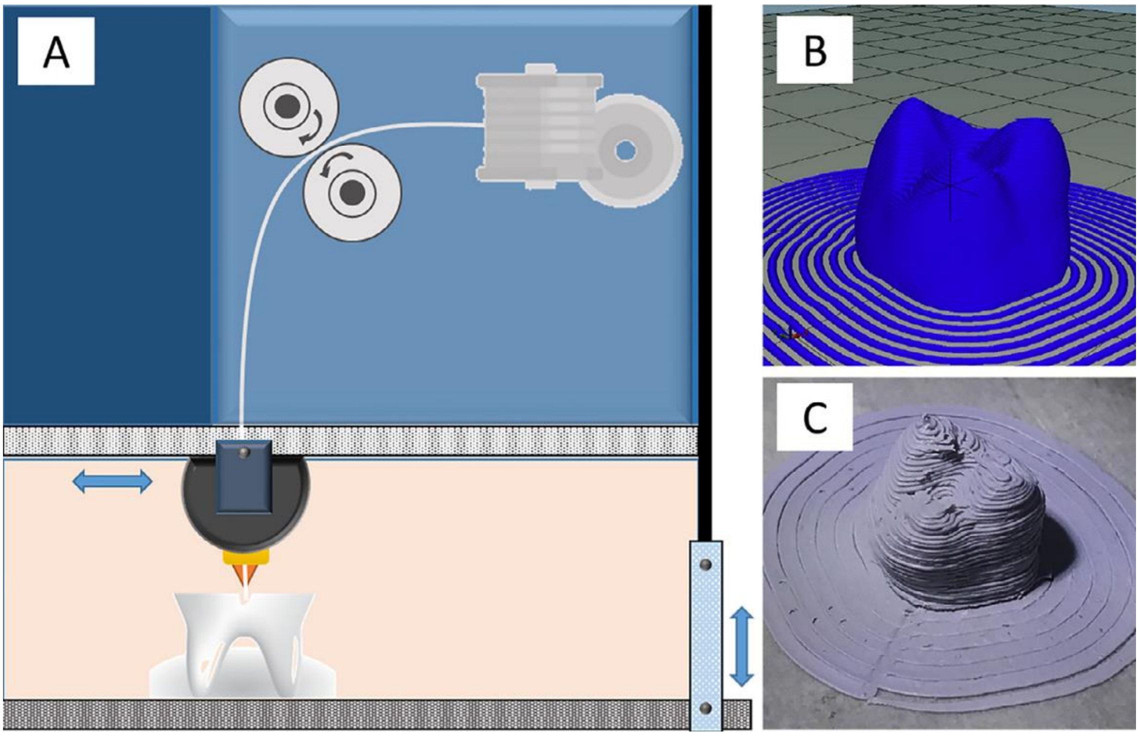

Figure 6. Fused deposition modelling (FDM) technology used in dentistry: (A) FDM printing in dentistry; (B) dental crown (CAD file); (C) dental crown (FDM printed piece). Reprinted with permission from Ref. [107].

Due to the low mechanical properties of the neat unfilled thermoplastic filaments commonly used in FDM, this technique is used only for the printing of temporary crowns and bridges in dentistry. Although the final product obtained by FDM is brittle and contains rough surfaces, this low-cost technology is used in machines with low maintenance and in scientific research [12].

Polymeric material blended with antimicrobial agents is another approach that is gaining popularity in the development of biofunctional FDM filaments. Notable work in this regard includes the development of PLA filaments featuring varying proportions of nitrofurantoin (NF) as the antimicrobial agent [265]. The antimicrobial evaluation showed that the NF release from the FDM printed sample resulted in antimicrobial performance that was sustained over seven days. PMMA and PLA mixed with gentamicin sulfate (GS) as the antimicrobial agent fabricated using FDM also showed significant antimicrobial properties [266]. Polymeric composites featuring antimicrobial metals such as zinc (Zn), copper (Cu), or silver (Ag) have also been explored for the fabrication of FDM filaments [267–270]. Research carried out by Muwaffak *et al.* [267] incorporated metallic antimicrobial agents such as Cu, Zn and Ag into PCL filaments for FDM printing. The results showed that the FDM fabricated material showed antimicrobial properties against *S. aureus* Gram-positive bacteria.

3.2. Engineering and architecture

FDM is used in engineering applications such as the production of microdevices [115,271], microfluidics [116] and electromagnetic shielding [139]. FDM is also gaining presence in automotive engineering primarily in new product prototyping which significantly decreases time to production [272]. Companies, like Porsche, use 3D printing to fabricate and reverse-engineer low-volume spare parts [273]. The manufacture of polyurethane foam parts developed using FDM printed molds [237] are used in racing cars such as Formula 1 (F1) [2,210]. Aerospace engineering applications include aircraft, drone parts and rockets [2]. However, the pieces manufactured with FDM have limitations like high porosity and poor mechanical properties [274]. This technology has been used, in aerospace engineering, to fabricate manufacturing tools, functional prototypes, concept models and some complex lightweight parts[238]. In most cases, the material used is UTLEM^{TM}, which is a high-strength thermoplastic [275].

During the COVID-19 pandemic, 3D printed face masks featuring air filters coated with functionalized graphene were developed using FDM (Figure 7) [22].

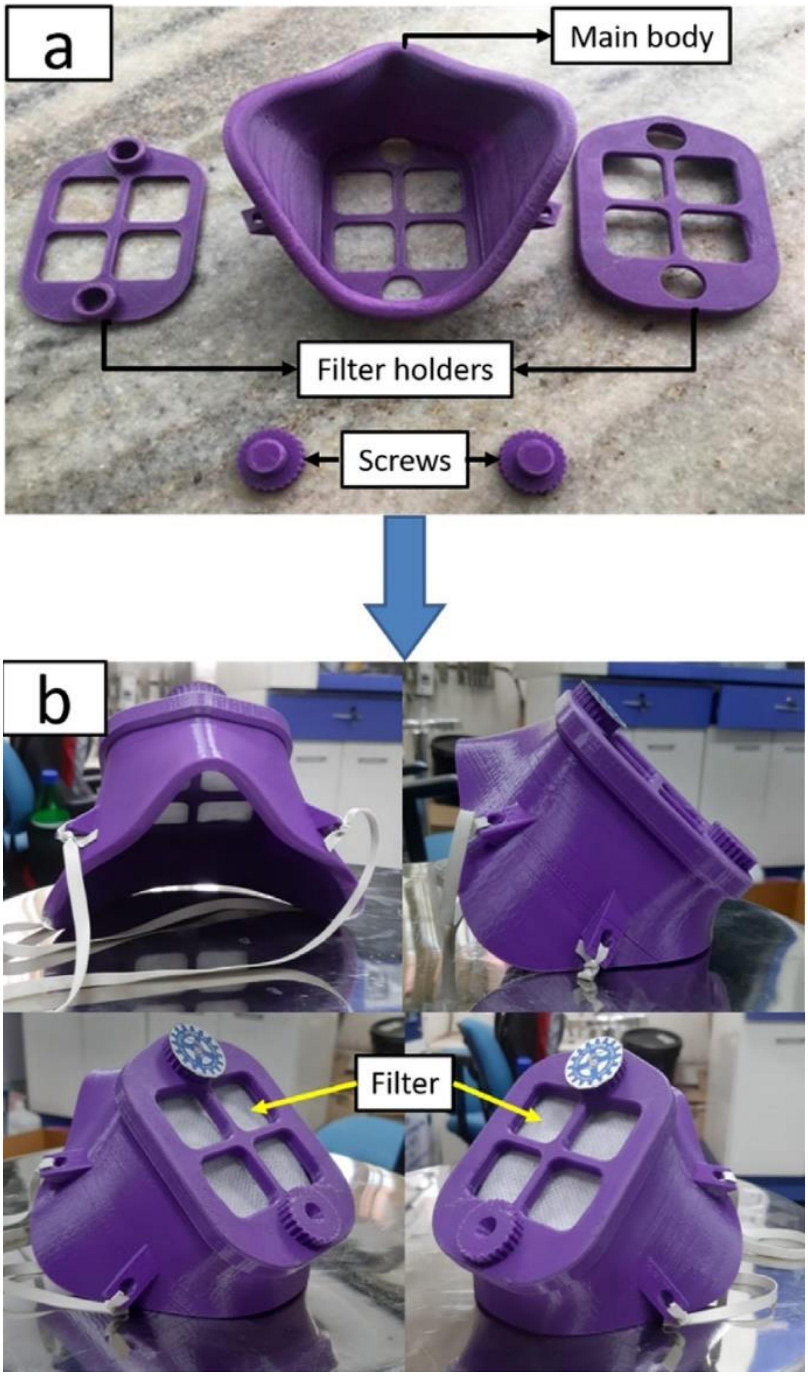

Figure 7. Face mask printed produced by fused deposition modelling assembled with a filter coated with functionalized graphene: a) parts of 3D printed face mask and b) 3D printed face mask with the filters coated with functionalized graphene. Reprinted with permission from Ref. [22].

FDM has also provided an alternative and accessible method to produce other PPE such as respirator face shields during the COVID-19 outbreak (Figure 8)[20].

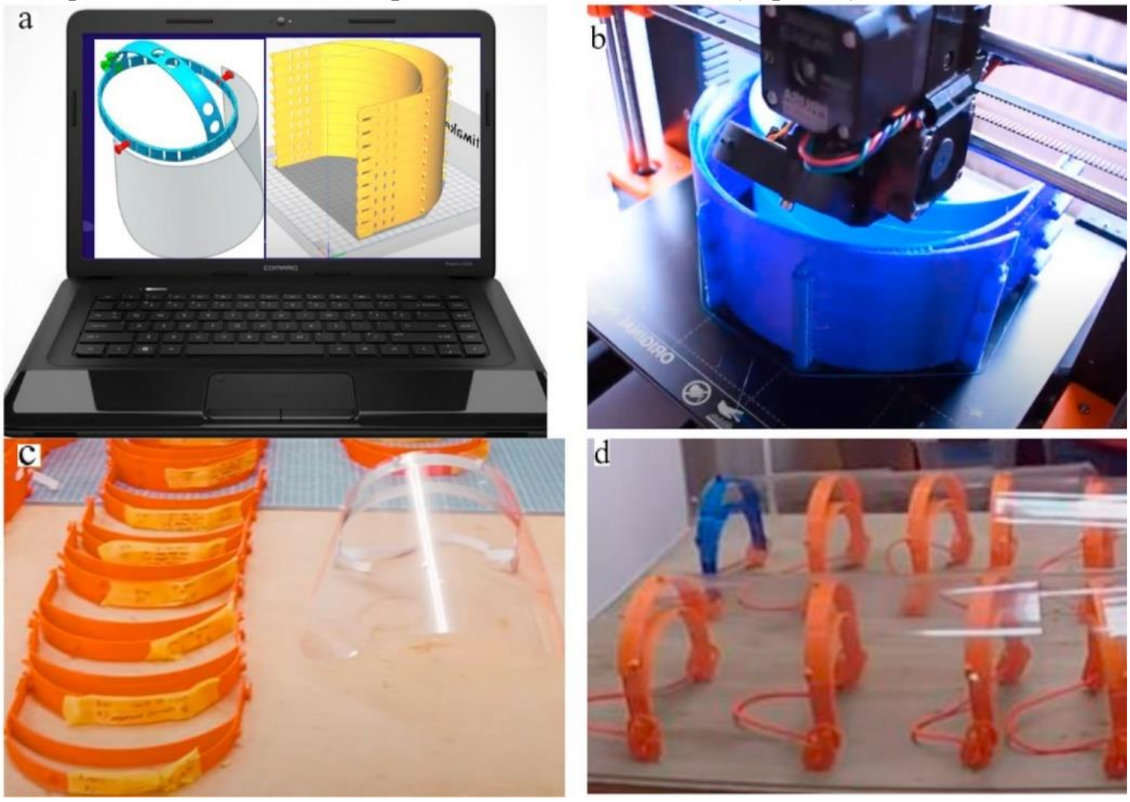

Figure 8. Respirator face shields fabricated by fused deposition modelling: (a) computer-aided design (CAD) of face shield holder and shield; (b) 3D printing procedure; (c) fabricated shield holder and shield pieces; (d) final fabricated respirator face shields after mounting the pieces. Reprinted with permission from Ref. [20].

Other devices have been fabricated by FDM during the COVID-19 pandemic such as ventilators and respirator systems, respiratory valves[20], and nasopharyngeal swabs for COVID-19 diagnosis [276,277].AM technology has also been used in the construction of houses [242]. This has many benefits like increased customization for architects, reduced construction time, reduced manpower, and construction cost [278]. In 2014, WinSun, in China, was the first architectural company that constructed a group of houses using 3D printing [279]. The selection of appropriate AM technology for construction applications is dependent on the cost, printing time, accuracy, and available materials [278]. For printing ceramics materials and concrete, contour crafting is usually used as the preferred printing technology. However, the FDM technology requires the use of polymer materials such as novel thermoplastics such as PEI, polyaryletherketone (PAEK), and polyphenylsulfone (PPSU)[242]. These high-performance thermoplastics are increasingly in demand for industrial-grade FDM construction applications, as they are a suitable, cost-effective, and lightweight alternative to some metals such as stainless steel or aluminium. FDM technology can use a printing material composed of polymers and synthetic stones [278] or Lecce stone scraps [280] to produce original industrial and building products. An entire FDM house has been built using a type of glass reinforced plastic, which is a light, solid, anticorrosion, anti-aging, waterproof and insulating composite material [243]. FDM construction has also been used to build other polymer-like models such as a space frame architectural model, Rotunda architectural model and

IBM Pavilion architectural model [281]. However, more research is necessary in order to improve large-scale FDM and multi-axis FDM [282]. Thus, Hack and Lauer patented a technique in association with the industry partner Sika Technology AG to robotically fabricate a series of 3D ABS mesh architectural formworks with a high capacity of precise spatial coordination (Figure 9) [282]. Thanks to the robot, the FDM printed mesh mould can be of varying sizes and cast with cementitious materials to meet different construction requirements.

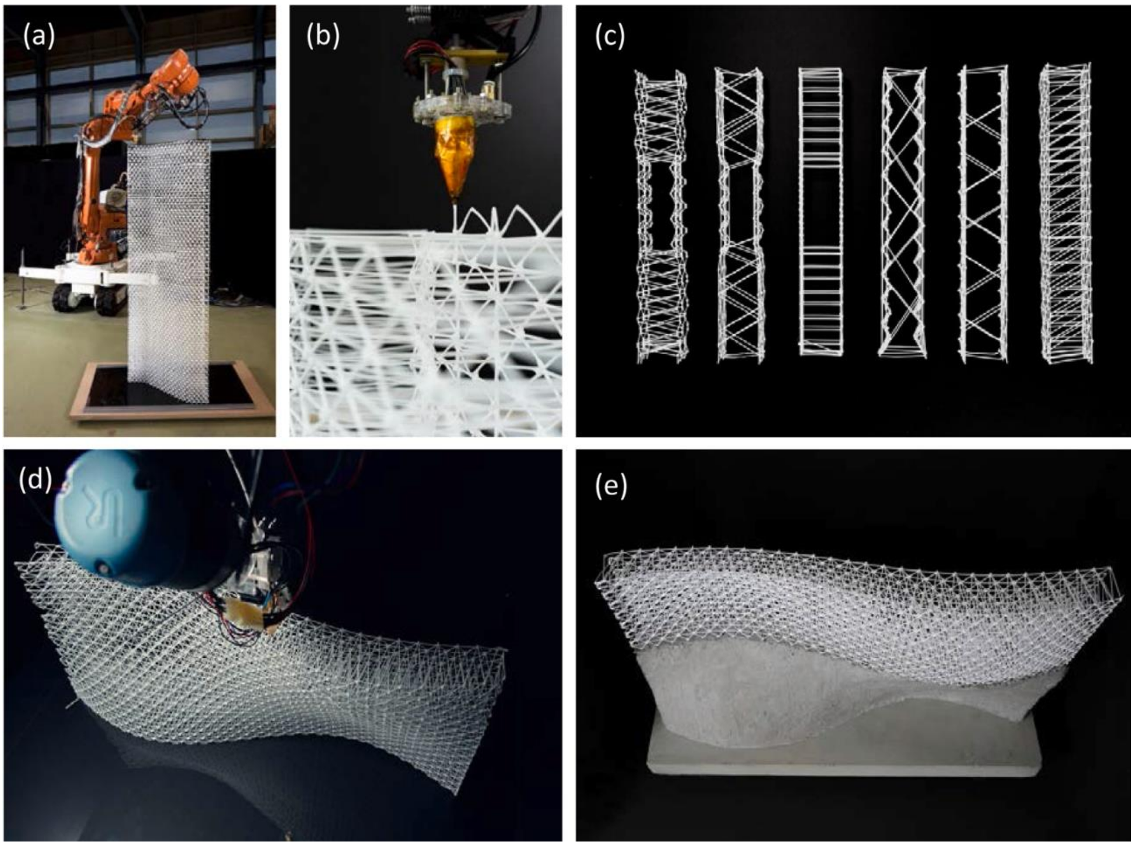

Figure 9. Spatial meshes fabricated by a robot based on fused deposition modelling (FDM): ((a), (b) and (d)) several views of the movable robotic arm-assisted FDM of lattice mesh; (b) several meshes robotically printed; (e) the printed acrylonitrile butadiene styrene (ABS) sample with sizes of approximately 80 × 60 × 8 cm was casted by concrete. Reprinted with permission from Ref. [282].

Another interesting application of FDM is the production of acoustic devices. Absorbing or reflecting sound waves is a requirement for many industries which calls for the cost-effective fabrication of porous, cellular and metamaterials suitable to be used as acoustic liners in engines, turbofans, ventilation and a range of other applications [283,284]. Low-cost 3D printing techniques such as FDM are vital in the development of functional acoustic devices. Although the conventional methods for the manufacture of foam and fibre like architecture are already available, their ability to customize the geometries for cellular architecture are restricted. This is where FDM offers a significant advantage, enabling the development of numerous complex architectures, targeted at either blocking or absorbing acoustic waves. Studies by Johnston and Sharma [165] used FDM to fabricate a fibrous sound absorber, which showed high sound absorption and allowed customization of peak sound absorption (Figure 10). Other acoustic studies using

FDM include the fabrication of a thermoplastic polyurethane (TPU) cellular absorber which resulted in high sound absorption coefficient at a targeted frequency range [239]. Huang *et al.* [240] on the other hand used FDM to fabricated a meta-fluid architecture inspired by cereal straws which resulted in predetermined resonance behaviour and enhanced acoustic performance. Sound attenuation of a periodic filter type architecture at the microscale, fabricated using FDM, also revealed their potential in broadband acoustic attenuation where the frequency of peak attenuation can be controlled by the distancing between adjacent meshes [241].

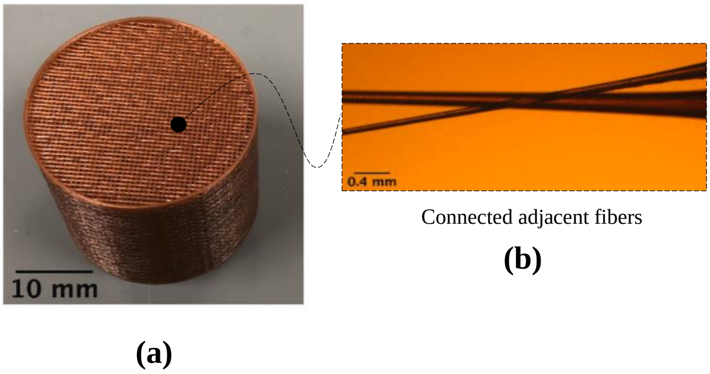

Figure 10. 3D printed acoustic device showing (a) the sound absorbing sample (b) Connected fibres of the adjacent FDM filament. Reprinted with permission from Ref. [165].

3.4. Textile industry and other fields

3D printing is also gaining popularity in the textile industry [123], for example, in the fabrication of various dresses, shoes and related products [285]. It has been demonstrated that single-face weft knitted fabric can be fabricated successfully by FDM, as shown in Figure 11 [285].

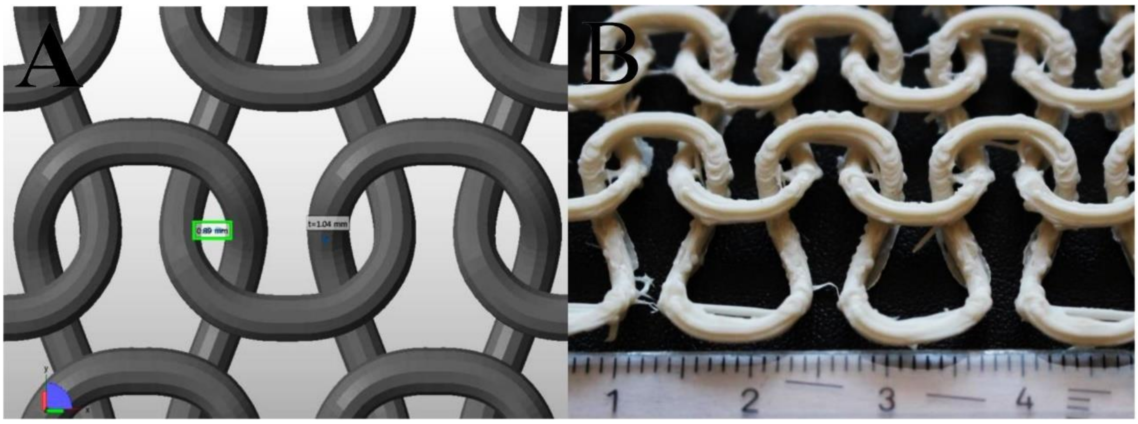

Figure 11. Single-face weft knitted fabric produced by fused deposition modelling (FDM): (a) CAD model of a single-face; (b) FDM printed fabric with soft PLA. Dimensions indicated by the ruler. Reprinted with permission from Ref. [285].

The primary factors in the textile industry when it comes to material fabrication, are properties such as good adhesion and stability [286]. FDM prints on cotton and polyester textiles have been shown to offer excellent adhesion properties [123]. Wood flour (WF)-filled PLA composite filaments have been developed for application in the fabrication of ornaments by FDM printing [153] (Figure 12).

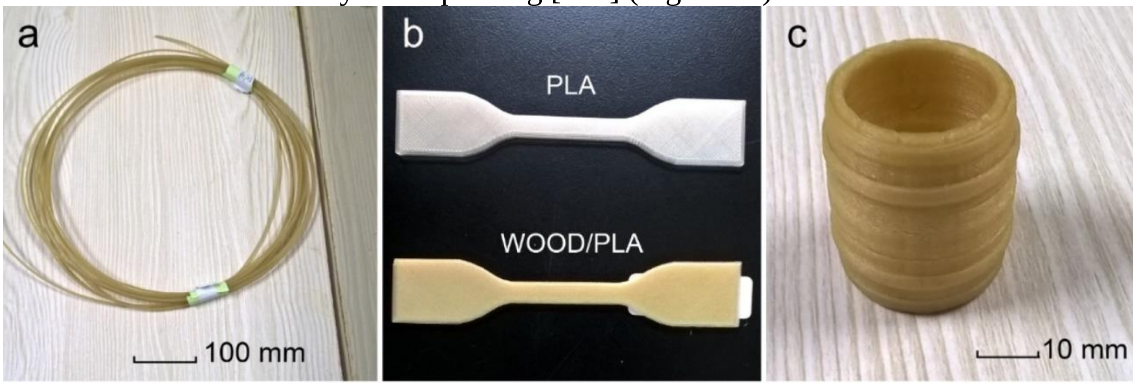

Figure 12. Filament, test specimens and 3D product: (a) Wood flour (WF)-filled PLA composite filaments; (b) mechanical testing specimens for tensile measurement; and (c) a barrel made WF-filled PLA fabricated by FDM printing. Reprinted in part with permission under a Creative Commons CC BY 4.0 License from ref.[153].

The results of this study showed that compared with pure PLA filament, adding WF changed the microstructure of the composite material, resulting in improved initial deformation resistance and a slight decrease in thermal degradation temperature and did not affect melting temperature.

FDM can also be used in other fields such as support filaments [161], prototypes [159], and in occupational therapy to manufacture aids for dependent people [244], among others.

4. Conclusions and prospects

Fused deposition modelling is one of the most popular AM techniques that allows cost effective fabrication of complex geometries informed by computer-aided design. This review presents the current status, the concepts necessary for the handling and operation of FDM printers, the industry standards of printing, the types of filaments used, the post-processing methods, and a broad range of applications. 3D printing has been predicted as the future industrial revolution. Even if this technology has some drawbacks such as printing only polymer-based materials, low printing speed in comparison with other AM techniques or imperfections in the final 3D printed pieces, the advantages of FDM far outweigh the limitations. This technology uses low-cost materials and allows the manufacture of complex designs with high reproducibility, suitable for parts in various colours, shapes, sizes, types, styles, materials, and functionality. Although FDM technology is still developing, progress in printing speeds and new materials is broadening its potential applications, which range from 3D printing full scale buildings to complex human organs with nanoscale features. In biomedicine, FDM is already being trialled to manufacture scaffolds for tissue regeneration and reconstruction. 3D printing of functional organs known as bioprinting, is also rapidly advancing and offers a promising future. Research groups around the world are working on overcoming the current limitations regarding the creation of complete tissues and organs *via* FDM, which require effective structural architecture that also acts as a viable environment for cells. FDM is also making inroads in applications such as the fabrication of bone models, drug release in pharmacology, biosensors, laboratory hardware, organoids, laboratory models, surgical tools, dentistry, microdevices, microfluidics, electromagnetic induction shielding, automotive and aerospace engineering, occupational therapy, architecture, construction, acoustics, textile industry, personal protective equipment and many other fields are also actively harnessing the great potential of FDM. The furthest scientific advances in the field include the combination of FDM with other technologies such as HME and the use of smart materials in 4D printing to produce functional smart objects that can perform active functions, which has opened a broad range of new FDM application fields.

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