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Suitability Analysis for Extrusion-Based Additive Manufacturing Process

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ABSTRACT

Additive manufacturing (AM) is a widely applied manufacturing paradigm used for the layer-by-layer fabrication of desired components and objects, especially for those with highly intricate geometry. Extrusion-based AM, which is a subcategory of AM processing technologies, is characterized by the facilitation of controlled and successive deposition of feedstock AM materials through the nozzles of printer heads onto a print bed. Extrusion-based AM processing enables design freedom but offers cost efficiency and process simplicity when compared to other AM categories i.e. liquid- and powder-based AM technologies. The extrusion-based AM process has become increasingly widespread over the last two decades because of the expanding material options that can be used in this technology, and its capacity to be hybridised through the addition of multiple printheads or incorporation into a secondary manufacturing system. Despite the promising aspects of the extrusion-based AM process, increasing demands for customised extrusion-based printed products and an expanding range of extrusion-based AM materials create both material- and process-related challenges that limit the suitability of extrusion-based AM processes for some specific applications. Consequently, the principal objective of this review paper is to conduct a suitability analysis of extrusion-based AM processes. The suitability analysis follows a review and discussion about the extrusion-based AM process, and an assessment of easy- and hard-to-print extrusion-based AM materials. This paper, therefore, provides a comprehensive suitability analysis of each extrusion-based AM process while also providing some promising ideas for improving their current suitability levels. The findings and ratings reported in this paper importantly offers viewpoints that would support better futuristic comparisons between developed and developing extrusion-based AM processes, especially as businesses look to adopt the right AM solutions.

Keywords: Extrusion-based additive manufacturing; Suitability analysis; Additive manufacturing materials; 3D printing

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1. Introduction

Additive manufacturing (AM), often called 3D printing, is described by The International Standards Organization/American Society for Testing and Materials Standards (ISO/ASTM 52900:2015) as the material joining process used to create desired parts with desired geometry and properties based on 3D model data, contrary to the formative manufacturing methodologies and

conventional subtractive manufacturing [1]. AM technology was initially invented by Hideo Kodama in 1980, who utilised ultraviolent light to consolidate parts to create desired 3D parts. After a decade, Charles Hull invented stereolithography (SLA) in 1991, then Crump developed fused deposition modelling (FDM) for polymeric materials. Soon after this development, Carl Deckard invented the direct metal laser sintering (DMLS) process, which is capable of additively processing metal powders – and was considered as a major milestone in the invention and development of the AM technology [2]. The AM technology is employed without the use of manufacturing operations such as tooling and fixturing. Therefore, this technology is frequently associated with the tool-free manufacturing [3]. AM technology also allows manufacturers and users to decrease both the production cost and lead time by offering lightweight AM systems, and automatically planning successive travel paths for layer-by-layer fabrication, respectively [4]. In this regard, the AM technology has recently emerged as one of the latest engineering interests because complex-shaped parts can be manufactured using the AM process, thanks to the design freedom and capability of part consolidation offered by this technology [5, 6]. AM technology is also capable of using various AM materials such as glass, ceramics, metals, and biomaterials in the form of powder, liquid, and solid feedstocks [7, 8]. This technology can therefore be classified into three subcategories as solid-, liquid- and powder-based AM processes. However, this classification is broad and includes some inconsistency because of the use of various AM materials in different physical states (i.e. liquid, wire, powder, resin, molten, solid, and filament) in the same AM process at the same time [9] as detailed in Section 2.1.1. Among the AM technology classifications, extrusion-based AM processes in which raw AM materials are melted-extruded-solidified as a result of the thermomechanical cycle of AM materials typically offer low-cost and simple processing operations in comparison to liquid- and powder-based AM processes [10].

Due to the merits of extrusion-based AM over the other two categories, a relatively growing number of scientific papers have been published over the last ten years i.e. between 2013 and 2023. Fig. 1(a) shows the number of publications (research and review papers) on extrusion-based AM as is available on the Scopus database focusing on either title, abstracts and/or keywords that included the words ''extrusion-based additive manufacturing'' or ''extrusion-based AM''. The research results were refined and grouped into review paper by selecting review, conference review and book chapter. Meanwhile, conference papers and technical papers were grouped into research papers. Fig. 1(b) was also created using the same searching strategy on the database of Scopus, and it shows the number of publications on the extrusion-based AM of some specific AM materials. For this search, the keywords of ''extrusion-based additive manufacturing of "x'' or ''extrusion-based AM of "x'' were used. Note that the letter "x" in the keywords represent each type of widely used AM materials including polymers, ceramics, food and energetic materials, biomaterials, composites, silicones, smart materials, glasses, photopolymers, woods, and construction materials.
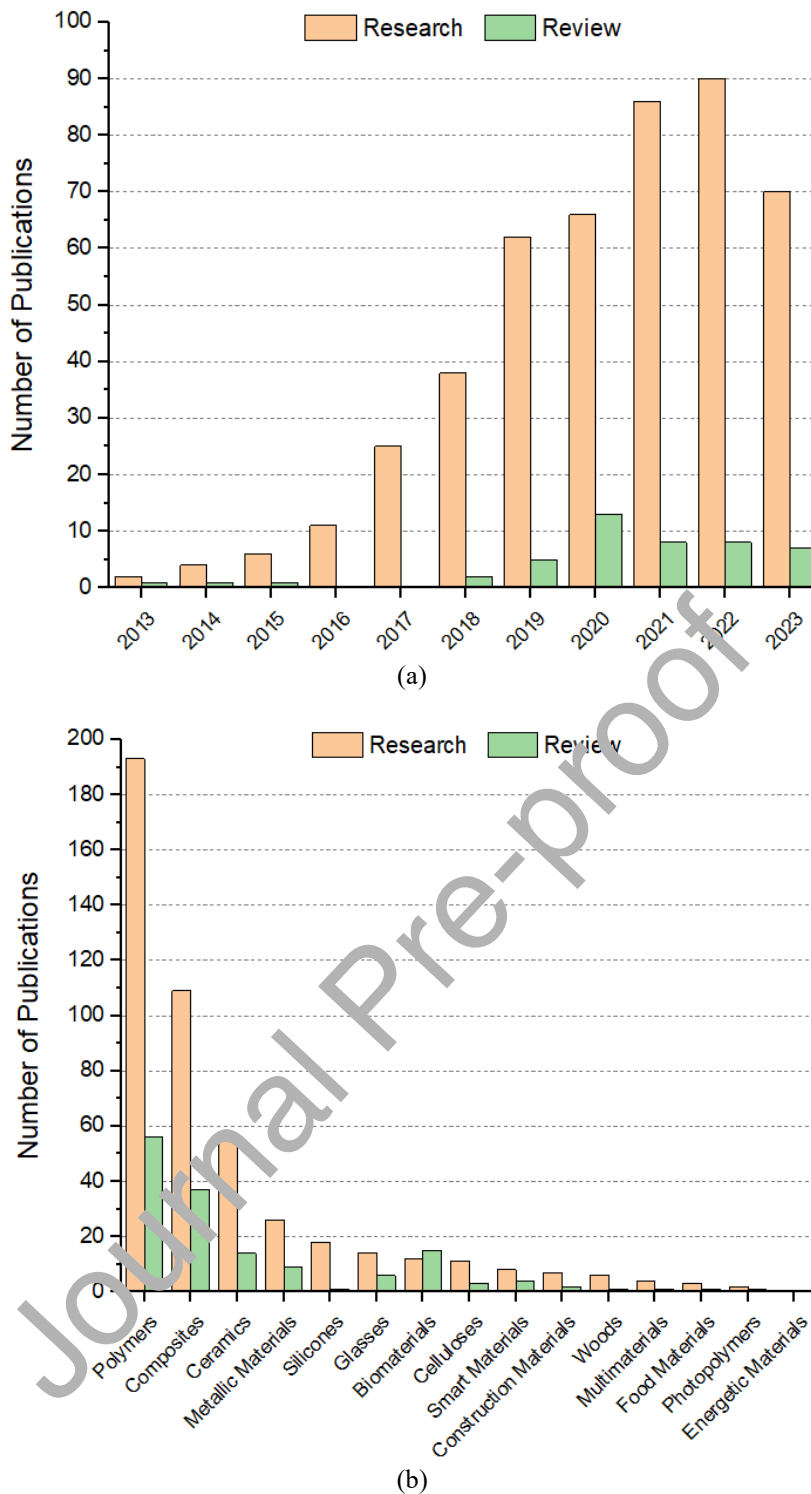
Fig. 1. Number of publications available on the database of Scopus on: (a) Extrusion-based AM; (b) Each type of AM materials processed by extrusion-based AM (data obtained for the last ten years i.e. between 2013 and 2023).

A wide range of AM materials have been currently used in extrusion-based AM processes, and the material range has been widening due to the latest developments in AM technology and material science. Contrary to these characteristic merits of extrusion-based AM processes, the technology still has material and process limitations, which significantly decreases the suitability of the extrusion-based AM process for some specific AM materials such as metals and glasses. Because

there is no available research fully focused on the suitability of the extrusion-based AM process, the main aim of this study is to close this research gap. Therefore, this paper briefly and systematically reviews the extrusion-based AM process, and then the existing and potential AM materials to be used in extrusion-based AM. This was done by highlighting extrusion-based AM process characteristics linked to specific material options, and further considering their process-centred suitability for achieving an eco-sustainable, efficient and effective extrusion-based AM process. This paper consists of six sections. Section 2 firstly includes the general information on the extrusion-based AM process, which is followed by its classification, characteristic properties, and merits over conventional manufacturing or alternative AM processes. Section 3 includes a review of easy- and hard-to-print AM materials that are currently available, being used, or tested with this technology, with interest in their level of adoption and potential suitability for extrusion-based AM. Next, Section 4 reviews the material- and process-centred suitability of extrusion-based AM. Lastly, Section 5 and Section 6 cover the discussions and conclusions drawn in the current paper respectively.

2. Extrusion-Based Additive Manufacturing Process

2.1. Classifications and characteristic properties of extrusion-based additive manufacturing

The AM technology can be classified into three subcategories as solid-, liquid- and powder-based AM processes based on the physical state of raw materials being used as shown in Fig. 2 [7]. Extrusion-based AM processes can further be categorised based on the method of material deposition, i.e. as filament-, plunger (also called syringe)- and screw-based extrusion AM processes. The core components of filament-based extrusion AM are the nozzle or printer head, feeding roller, building platform (also called print bed), and heater, as depicted in Fig. 3(a). In this extrusion-based AM method, feed rollers push the filament-form AM material to the heater where these materials are melted before being transferred to the nozzle. The nozzle is associated with the material discharge thereby materials can be printed layer by layer onto the building platform. The temperature of AM materials at the nozzle is to be higher than their melting points to facilitate material flow through the nozzle. In plunger-based extrusion AM processes (Fig. 3(b)), instead of rollers, a plunger is used to push the AM material to the heater. At this stage, AM materials can be melted to enable proper flow through the nozzle. Hence, the layer-by-layer printing of AM materials is identical with that of a filament-based extrusion AM process. In the screw-based extrusion AM process (Fig. 3(c)), a screw is used to push AM materials, providing a continuous pump of AM material towards the nozzle, which further aids the successive material deposition and layer-by-layer printing process [11]. The screw-based extrusion AM process subcategory of extrusion-based AM processes is the easiest to use because the heating rate and material feedstock is more controllable and reliable when compared to the other two subcategories of extrusion-based AM processes [12]. In the early 1990s, various AM processes were broadly categorised, based on the initial physical state of raw AM materials that exist as solid-, powder- and liquid-based materials [13, 14], as shown in Fig. 2.
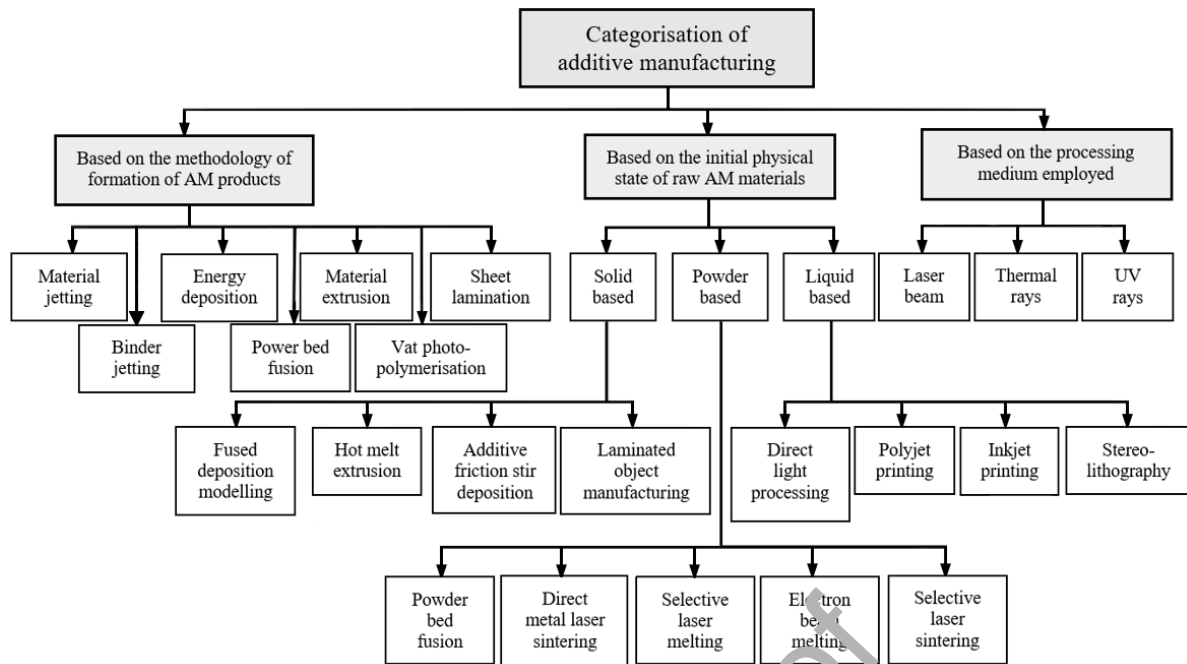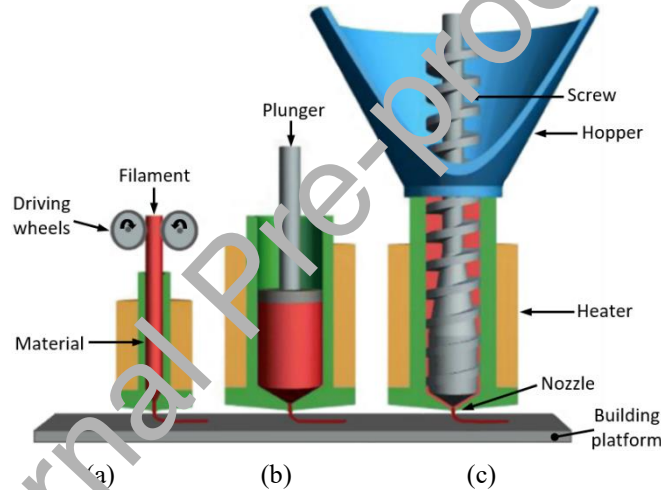
Fig. 2. Categorisation of AM technology

Fig. 3. Main components of extrusion-based AM process types: (a) Filament-based; (b) Plunger-based; (c) Screw-based extrusion.

The categorisation of AM processes on the basis of raw materials being used (i.e. solid-, liquid- and powder-based AM process) has some inconsistency, since this categorisation was made based on a very broad generalisation. The reason for not being able to categorise AM processes reliably can be associated with the possibility of using various AM materials in different types of AM processes at the same time [9]. For instance, the raw AM material groups that include "wires and solid filaments", "photopolymers and molten materials", and "metal powders" are often linked with solid-, liquid- and powder-based AM processes respectively. However, the first raw material group (i.e. wires and solid filaments) also includes sheet materials that can be used in laminated object manufacturing (LOM) and sheet lamination (SL), while the second group (i.e. photopolymers and liquid materials) can also be rephrased as photopolymers and metallic materials in molten or liquid state, which includes photopolymers that are fully liquid polymers and used in stereolithography (SLA), which does not process molten thermoplastic polymers. Regarding the third raw material category (metal powders), powder-based AM processes such as selective laser melting (SLM) and electron beam melting (EBM) use powders as raw AM materials that are in solid state; however,

these AM processes are characterised by the fast solidification and phase formation of molten (liquified) powders melted by an energy source e.g. laser and electron beam. The third category (powder-based) can also involve the wire direct energy deposition (wire-DED) or wire+arc AM (WAAM) through which metallic powders in wire form are melted then deposited in molten state. However, these two AM processes better fit the first category (i.e. solid filaments or wires, while powder-DED better fits the third category (i.e. metal powders). Moreover, these beforementioned AM categories only takes two material classes i.e. photopolymers (liquid) and metals (powder) into account, and not a broad range of different AM material types such as thermoplastic and thermosetting polymers, elastomers, ceramics (including sand, etc.), papers and celluloses that are usually used in the original laminated object manufacturing (LOM) AM process [9]. This AM technology, i.e. LOM, characteristically softens or melts raw AM materials in the state of filament or wire, then extrudes these materials to form deposits on the building platform where AM materials are printed layer by layer until the fabrication is complete [15].

As a result of the broad classification of AM process made based on the physical state of raw AM materials, all the recent commercial AM processes were categorised by the standard of ISO/ASTM 52900:2015 to form seven main AM process technologies which include: material extrusion (ME), directed energy deposition (DED), powder bed fusion (PFB), vat photopolymerisation (VP), sheet lamination (SL), material jetting (MJ) and binder jetting (MJ) [16] as shown in Fig. 2. Another attempt on the categorisation of AM process can be made on the basis of the medium (heating or melting energy source) that are used to process the raw AM materials as laser beam (or electron beam), thermal means (e.g. thermal radiation) and ultraviolent (UV) rays (e.g. microwaves). In addition to these current categorisation of AM technology, the whole family tree of rapid prototyping and AM processes were also recently classified by the German production standards (i.e. DIN8580 and DIN8581), and Helsinki University of Technology as shown in Table 1 [17].

Table 1. The whole rapid prototyping tree [17]; note that AM processes in the table include not only commercial methods but also methods under research.

Solid materials	Powders	Liquids	Sheets
Fused deposition modelling (FDM)	Selective laser sintering (SLS)	Solid ground curing (SGC)	Laminated object manufacturing (LOM)
Melted extrusion manufacturing (MEM)	Direct plastic/metal laser sintering (DMLS)	Design-controlled automated fabrication (DESCAF)	Curved-layer laminated object manufacturing
Multi jet modeling	Selective laser sintering of ceramics	Rapid micro product development (RMPD)	Slicing solid manufacturing (SSM)
3D plotting	Selective laser reaction sintering (SLRS)	Stereolithography (SLA)	Laser profiling machine (LPM)
Ballistic particle manufacturing (BPM)	Direct metal fabrication (DMF)	Solid laser diode plotter system (SLP)	Paper lamination technology (PLT)
Contour crafting (CC)	Laser-aided powder solidification / powder jet (LAPS-J)	Solid object ultra-violet laser plotting (SOUP)	Computer-aided manufacturing of laminated engineering materials (CAM-LEM)
Droplet welding (DROW)	Direct light fabrication (DLF)	Solid creation system (SCS)	Trusurf
Shape deposition manufacturing (SDM)	Laser aided direct rapid prototyping (LADRP)	Soliform	Offset fabrication
Photo chemical machining (PCM)	Topographic shell fabrication (TSF)	Unirapid	JP System 5
Recursive mask and deposit MD	Lasform	Direct photo shaping (DPS)	Staratoconception

There are several types of a developed extrusion-based AM process. Among all types of extrusion-based AM processes, FDM is one of the most widely used extrusion-based AM process in which the deposited raw material is in the form of a filament. This AM process, in some cases, necessitates support structures to facilitate the fabrication process, particularly in cases where a desired object has sections that form angles of less than 45º from the building platform, called overhangs. As a result, the removal of support structures may be challenging after the fabrication is complete, and may damage the final parts [18]. As mentioned before, the extrusion-based AM process is mechanically simple and an easy to operate technology requiring low-cost production tools and equipment [10]. However, this technology has several challenges such as unsatisfactorily low surface finish, low dimensional accuracy and resolution, low structural integrity and mechanical properties from the *Z*-axis which is the printing direction perpendicular to the building platform, and insufficient bonding of printed layers [19]. Because of these challenges and drawbacks of this technology, rigorous post-processing of extrusion-based AM processed parts is a requirement [9, 20]. These characteristic properties, merits and challenges of the extrusion-based AM process differentiates this technology from liquid and powder-based AM processes [21]. On the other hand, the extrusion-based AM technology also offers different capabilities when compared to conventional subtractive manufacturing methods as discussed in the next section.

2.2. Characteristics of extrusion-based additive manufacturing process

2.2.1. Merits and demerits of extrusion-based additive manufacturing

The specific merits of extrusion-based AM, contrary to powder- and liquid-based AM, are prevalently associated with its cost-effectiveness and broad range options of materials to be processed using this technology; mainly including polymers, ceramics, food and energetic materials, biomaterials (including ceramics or ceramic-based composite biomaterials), composites, silicones, smart materials, glasses, photopolymers, woods, and construction materials [22]. Extrusion-based AM is associated with cost-effective fabrication of desired parts because of: (i) not using costly equipment and heat sources (such as lasers, electron beams and UV rays), (ii) not using AM materials in the form of powder that are costly to buy and store, (iii) not using an enclosed building chamber (except FDM) that increases the complexity of process control and cost of equipment, and (iv) not using complex equipment for material deposition i.e. only ram, driving wheel or syringe can be used to apply relatively low amount of pressure to force the liquid/softened AM materials through the nozzle of print heads, which in return lowers the total cost of fabrication. Moreover, feedstock AM materials can be used in various forms in extrusion-based AM processes, such as in the form of a wire (wire-DED), paste (paste extrusion modelling), pellet i.e. compressed mass (fused granular fabrication), liquified material in a syringe or container (DIW), and filament (FFF and FDM). Since extrusion-based AM has basic set ups and not complex equipment, this manufacturing technique is popularly combined with a gantry or robotic arms for the high-volume mass production particularly in the food and construction industries [23]. The basicness of mechanism of extrusion-based AM process also allows the hybridisation of this technique by incorporating the base extrusion-based AM process with additional filaments or print heads; thereby increasing demand for the highly customised multimaterials with high functionality processed by extrusion-based AM [8, 24].

The advantageous side of extrusion-based AM, for example, is in the use of direct ink writing (DIW), as this type of extrusion-based AM does not require elevated processing temperatures for

their operation. The capability of DIW to run at low processing temperature, such as room temperature (RT), makes DIW technique a very suitable technique for photopolymers to be AM processed as the temperature-sensitive molecular chain and chemical structure of photopolymers can be distorted at the levels of processing temperatures above RT [8]. Meanwhile, significantly elevated temperatures above RT in FDM and fused filament fabrication (FFF) technologies are typically required to achieve the desired material processability as these extrusion-based AM processes are normally used to fabricate desired parts made of AM materials whose melting points are significantly higher than RT such as metals and polymers. Some other merits of extrusion-based AM processes include the simplicity of operation and a less-constrained operational environment, which thereby allows for mass adoption, and the ability to utilise such technologies across different shop floor areas; a case for which other AM technologies may face more surrounding environmental constraints [25, 26]. Having highlighted the relevant merits of extrusion-based AM, the main demerit of extrusion-based AM technology can be associated with its currently achievable printing accuracy and resolution, which is highly dependent on the diameter and geometry of nozzles being utilised. Therefore, as the size of desired parts become smaller, the capability of achieving print accuracy becomes more challenging. In these cases, extrusion-based AM may not be competing with other AM technologies regarding the demand for high printing accuracy. Such a disadvantage of this manufacturing also makes the printing of some specific components such as aerospace components like engine parts highly challenging as the aerospace authorities and leading aerospace companies generally demand the dimensional accuracy of less than 10 μm [27]. This high demand on the printing accuracy makes powder-based AM processes more suitable manufacturing technique than extrusion-based AM as the printing accuracy of few microns cannot be currently achieved using extrusion-based AM [28, 29]. The nozzle clogging is another specific demerit of extrusion-based AM process leading to low dimensional accuracy. This problem can be overcome by increasing the diameter of nozzles of print heads; however, the increased nozzle diameter impairs the printing accuracy [30]. Other demerits of the extrusion-based AM technology may be associate with its temperature dependence and the challenges associated with processing high-temperature and volatile materials across various environmental settings like in schools or open shop floor areas, as this may pose health and safety hazards [31]. Extrusion-based AM is also not capable of printing parts having angles of ≥45° to the print bed (where the first layer or platform adhesion if necessary is deposited to build desired parts on the layer-by-layer basis) without supporting overhang sections of desired parts with a support structure. The overhangs sections of parts being extrusion-based printed require the use of vertical support structure that requires post-processing to be removed [17].

Widely used commercial extrusion-based AM processes include FDM, FFF, DIW, robocasting, 3D concrete printing, composite filament fabrication, melt extrusion manufacturing, ceramic on-demand extrusion (CODE), fused deposition of ceramics and bioprinting. In addition to specific beforementioned features of extrusion-based AM, each type of extrusion-based AM process has their own boundedness. For instance, even though FDM can be applied to most of the commercially available AM materials (e.g. thermoplastics, ceramics and metallic materials) that can be softened or melted above RT. The fabrication of desired parts is fabricated in an enclosed (and often vacuumed) building chamber to achieve higher mechanical properties (higher bonding strength and dimensional accuracy) due to improved layer adhesion and significantly reduced amount of shrinkage of FDM-processed parts due to the elimination of temperature difference between the printing temperature and temperature of building environment [32]. However, the application of enclosed building

chamber is a limitation in the building volume that a printed part processed by FDM can maximum have [33]. In contrary, FFF has not a closed building volume restricting the maximum building volume, but the deposited AM materials in FFF experience the temperature difference and fast solidification, which may lead to shrinkage, inconsistency in dimensions and metallurgical defects such as hot cracking. FFF can be applied for materials that can be fabricated using FDM and has a very high capability to be integrated in multimaterials printing and hybridised by incorporating a secondary manufacturing process into the based FFF process. DIW is popularly applied for biodegradable and biocompatible materials and celluloses as these AM materials do not necessitate high printing temperature to be softened or molten to be deposited layer by layer. Robocasting is another widely used extrusion-based AM process that the fabrication of desired parts using this process do not include solidifying or drying, but the material options to be used inn robocasting is mainly limited metals, ceramics and bioceramics. Melt extrusion manufacturing (MEM) has a limitation related to the printing temperature that only biomaterials and polymeric materials can be printed using this process as the printing temperature of MEM cannot exceed the glass transition temperatures of these AM materials. There are other extrusion-based AM processes that are developed for the fabrication of some specific AM materials, which is why these extrusion-based AM processes have limited application areas due to the limited material options that can be used in these extrusion-based AM processes. For example, the application areas of 3D concrete printing, composite filament fabrication, ceramic on-demands extrusion and bioprinting are limited only to cementitious materials, composites, ceramics and biological materials (e.g. human tissues and cells) respectively [8].

2.2.2. Merits over powder- and liquid-based additive manufacturing processes

The material-centred suitability of AM material powders that can be used in a powder-based AM processes, e.g. SLS, SLM and DMLS, is highly limited to some factors such as the morphology (mean shape, size distribution, and chemical composition of powder particles) and characteristics of powders. In this regard, AM powders produced by means of gas and water atomisation methods have more spherical particle morphology that makes these types of powders more in balance. In powder-based AM processes, the powder should have uniform and carefully selected chemical and mechanical characteristics such as uniform particle size distribution of powders in the powder bed, uniform powder shape and morphology, and packing density (i.e. powders must be properly mixed to minimize the potential voids among powder particles) [34]. These characteristic properties of powders are essential and should be carefully selected for repeatable, reliable, and consistent fabrication of desired parts in powder-based AM processes [35]. The suitable properties of powders result in an easy-to-flow feature of the powder during transfer to powder bed, and aids the fabrication process, thereby leading to more stable parts following the sintering and debinding processes [21, 36]. However, achieving optimal structural, chemical, and mechanical powder-particle characteristic is difficult and costly to achieve considering the rigorous requirements to store AM materials in the form of powder. Alternatively, the powder particles used in a filament-based extrusion AM process typically necessitates fine powder particles with an average diameter less than 20 μm to improve flowability during the extrusion deposition of AM materials. The filaments can be composited including several binders and powders to improve the properties of desired parts processed by extrusion-based AM. In this regard, spherical powder particles are the most preferable powder geometry while preparing filaments; since spherical particles help achieve better surface finish and avoid particle interlocking while being deposited through the nozzles of print heads.

Compared to liquid- and powder-based AM processes, the extrusion-based AM process can be associated with low-cost equipment and production cost [37], while costly resources like lasers, electron beams, powder material, and the storage that requires keeping the oxygen and humidity levels under control [38].

2.2.3. Merits over subtractive manufacturing processes

Extrusion-based AM process is characteristically different from conventional manufacturing processes, e.g. milling, CNC machining, and grinding, in several points wherein undesired materials are removed from the workpiece. The main differences are the potentially achievable production speed, geometric complexity of parts, accuracy and programming as discussed by Ref. [39]. Although the extrusion-based AM technology was initially developed for polymeric materials, the material options to be used in extrusion-based AM processes have expanded to include other AM materials (e.g. metals, food materials, woods, glasses, smart materials, construction (i.e. cementitious) materials, biomaterials, composites, various polymeric materials, plastics, ceramics and ceramic-based composites, and highly customised multimaterials). Among these AM materials, only very few of these AM materials can be produced using powder-based AM. In this regard, conventional manufacturing methods such as CNC machining can possibly be used for only few polymers and soft materials like machinable foams and waxes, whereas AM process has far larger scale of material option to be used in the AM technology. Moreover, conventional manufacturing methods are generally a lot faster compared to extrusion-based AM processes when considering production time for the same volume of material. However, the fabrication of desired parts using extrusion-based AM processes are completed in a single stage that requires simpler pre-processing steps that includes machine set-up [40]. On the other hand, manufacturing with conventional production methods is a multi-staged procedure that involves more extensive process planning and relocation of parts for final product assembly [41]. Although the extrusion-based AM process takes more time to be completed, this technology can help eliminate the need for multiple parts and assembly during the fabrication of desired products, mainly by incorporating parts and assemblies through better modular designs [42]. Regarding raw material waste, which involves the removal of unutilised raw material (such as in chip formation and trimming), conventional subtractive manufacturing generates significantly more waste [43]. On the other hand, extrusion-based AM process significantly minimizes raw material waste as shown in Fig. 4 by resulting in only small amount of waste in post-processing stage (if necessary), and as platform adhesion and support structure for overhangs.
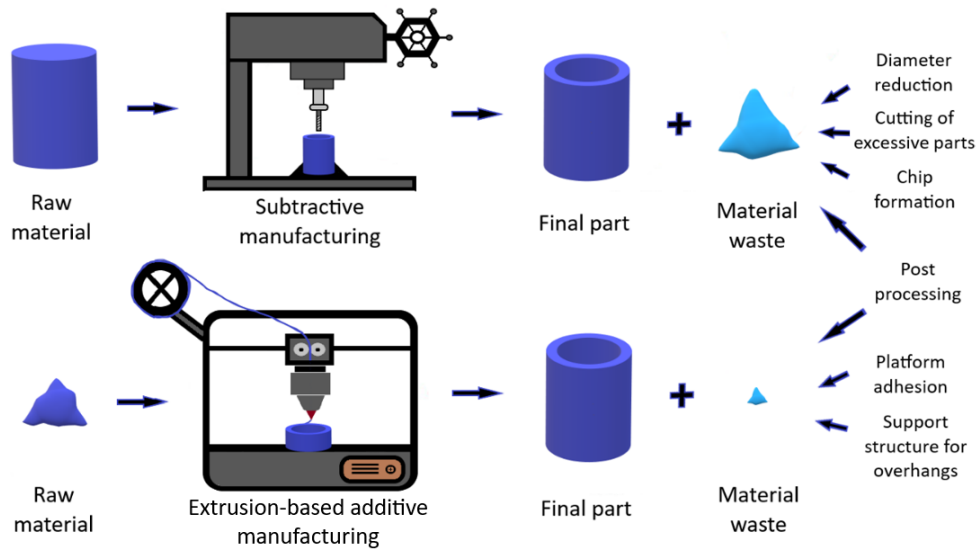
Fig. 4. Comparison of material waste between subtractive manufacturing and extrusion-based AM process.

Geometric complexity and design freedom are some other characteristic merits of the AM process, which leads to an increase in the adoption of this technology over conventional manufacturing methods. Specifically, the reason why an extrusion-based AM process offers the production of parts with complex geometry is because the layer-by-layer material deposition process enables any geometrical feature to be fabricated. In this regard, while some geometric features cannot be manufactured by using CNC machining operations, geometrical internal features and undercuts can be manufactured using the extrusion-based AM process, and without an extensive process planning [18]. AM machines also simplify complex 3D problems to basic 2D cross-sections by removing the connections of surfaces. In CNC machines, simple geometries such as cones and cylinders can be easily defined for the joining of points located in a path. However, these points can be rather close to each other in freeform surfaces along various orientations that makes undercuts, sharp internal corners and other complex features not possible to produce by conventional manufacturing methods. Because the simplification generally cannot be completed in conventional manufacturing methods, CNC machines mostly fail if these complex geometries are beyond the limit [39]. Process planning and the determination of program sequence of CNC machines can be very detailed compared to AM machines including machine speed setting, positioning and selection of the tool. Lastly, any error or programming in AM process results in an improper building; however, any incorrect programming in CNC machines leads to more severe damages in the worst scenario that may endanger not only machines but also the life of operator [39]. In contrast to tool-free extrusion-based AM processes, tool wear is another main problem of conventional manufacturing process that cutting tools are generally coated with thin multilayers to decrease the amount of heat entering into the cutter, which helps to extend the lifespan of cutting tools. However, the coefficient of thermal expansion mismatch that exists among the different thin coatings of a cutting tool is the main reason for low machining efficiency and premature tool failure, which leads to increased manufacturing costs [43].

The ecological impacts of the manufacturing system applied is another critical factor that determines the impacts of its processes on the environment, with respect to climate change, land use and toxicity. By considering these impacts, hobbyists and manufacturers can decide about adopting and using AM technologies rather than conventional manufacturing technologies or vice versa, in

order to minimise certain undesirable impacts of the manufacturing processes. The most common ecological factor that both conventional and additive manufacturing processes use is the significant amount of electricity required, which is a time-dependent factor, which is also highly dependent on the desired part (surface finish and geometric) quality to be produced. However, the choice of tooling and tooling operation can be done in a strategic way can significantly reduce these times. One other main difference between extrusion-based AM and conventional manufacturing processes is that material removal in conventional machining operations normally use cutting oil as a lubricant, which can be associated with an extra source of waste that contributes to atmospheric and aquatic pollution [44].

3. Widely Used Additive Manufacturing Materials and Extrusion-Based Additive Manufacturing Processes

Extrusion-based AM processes form one of the most suitable (as reviewed in Section 4) and applicable set of manufacturing methods for processing existing and potential AM materials, e.g. polymers, polymer-based composites, construction materials and biomaterials (including ceramics or ceramic-based composite), for wide-reaching applications. By the end of Section 3, the AM materials that can be used in extrusion-based AM processes are categorised as easy- and hard-to-print AM materials, with each material class/ or type briefly reviewed to highlight their current and potential level of applicability for an extrusion-based AM technology.

3.1. Easy-to-print additive manufacturing materials

3.1.1. Polymers (thermoplastics and composites)

The first extrusion-based AM process invented, i.e. FDM [45], was designed for only two polymeric materials, which are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Since then, polymers have been one of the most widely applied AM materials for extrusion-based AM processes. This class of materials can enable the production of lighter products, and use of more energy-efficient processes making these AM materials a very important part of the society and environment. So far, thermoplastics and elastomers are the only commercially available polymeric materials for extrusion-based AM [46, 47]. Employing thermoplastic polymeric materials in extrusion-based AM processes is the most common approach for achieving low cost, and the easing of handling and processing [31]. Furthermore, as part printability and functionality have been achieved using thermoplastics polymers, this is also the target for other material systems. However, achieving the desired printability and part functionality is dependent on the high-level control of through-process material properties and 3D printing (3DP) specifications [48]. Environmental (thermobaric) effects, however, present in a chosen setup for extrusion-based AM should not be ignored. Fig. 5 shows the relevant factors that contribute to the ease of printability and part functionality of an AM material in extrusion-based AM technology. These factors significantly contribute to achieving and controlling the effective material flow during printing, while ensuring that the extruded layers bond effectively to the preceding layers to achieve the desired shape, structure and part functionality [49].
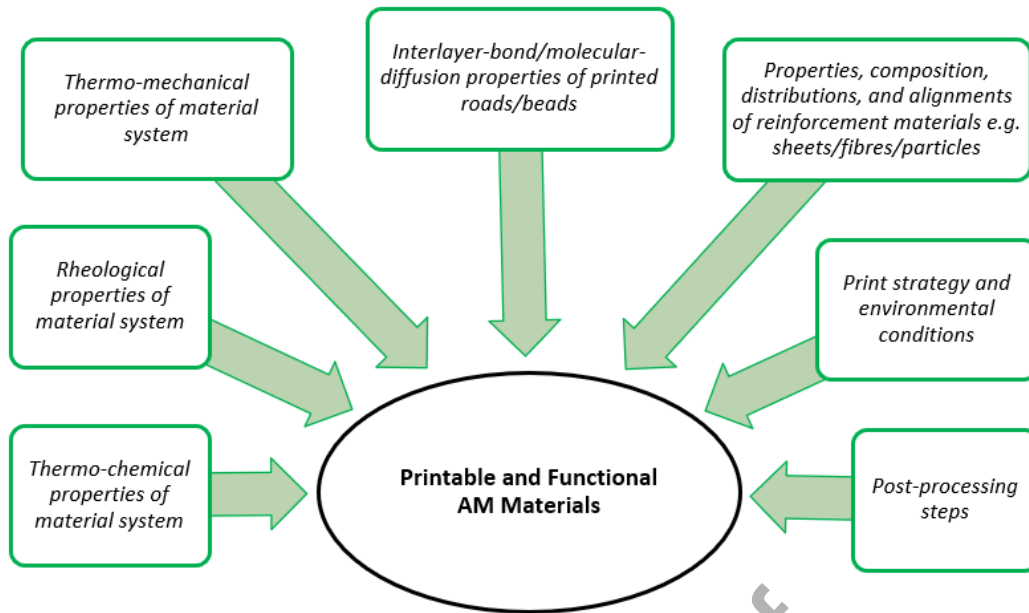
Fig. 5. Important controlling factors for printability and part multifunctionality in extrusion-based AM process.
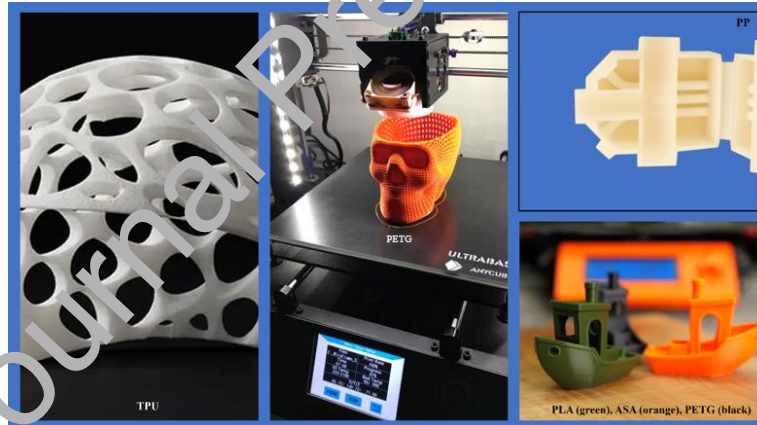
3.1.1.1. Thermoplastics

As mentioned earlier, thermoplastics are one of the most easy-to-print polymeric-based AM materials to be processed by extrusion-based AM, using a printer head to liquify and then extrude the molten material for layer-by-layer material deposition. Alternatively, thermoplastic resins that do not require elevated temperatures to flow can be printed using DIW extrusion-based AM process. However, post-processing steps are usually required to ensure that parts fabricated via FDM/DIW technologies achieve a desired near net-shape and part functionality. Standard (ABS and PLA), engineering (polycarbonate (PC) and Nylon) and high-performance thermoplastics are developed, and commercially available polymers used in extrusion-based AM process [50]. Pellet and filament materials are also practically applicable in FDM (filament-, plunger- and screw-based) machines, thereby increasing the scope of applicable thermoplastic materials for extrusion-based AM technologies. Table 2 includes a list of the commercially available thermoplastic materials that can be used in extrusion-based AM processes as offered by Stratasys – leading providers of AM machines and filament materials.

Based on the descriptions of such filaments shown in Table 2, it appears that thermoplastic pellets and filaments with useful mechanical, electro-dissipative, biocompatible, thermal and chemical properties have been developed for FDM/FFF extrusion-based AM processes. However, there is a limited range of biobased and biodegradable thermoplastics and elastomers that are validated and commercially available for not only FDM/FFF extrusion-based AM process, but also for DIW extrusion-based AM. Fig. 6 shows some of the extrusion-based AM-processed and eccentrically shaped structures of common polymeric AM materials like polypropylene, TPU and PLA.

Table 2. Commercially available thermoplastic polymers for extrusion-based AM process [51, 52].

Application class	Thermoplastic types	Example of filaments materials offered by Stratasys	
Standard	ABS, PLA, polyethylene terephthalate glycol (PETG), polypropylene (PP), HIPS (high impact polystyrene)	ABSplus ABS-M30 ABSi ABS-M30i™	ABS-ESD7 ASA (acrylonitrile Styrene acrylate) PLA
Engineering	Poly carbonate (PC), thermoplastic urethane (TPU), nylon	PC-ABS PC-ISO™ (Polycarbonate-ISO)	Nylon 6™ Nylon 12 ™ FDM™ TPU 92A
High-Performance	Poly ether imide (PEI), poly phenyl sulfone (PPSF/PPSU), polyether ether ketone (PEEK), polyether ketone ketone (PEKK)	ULTEM ™ 9085 (PEI) ULTEM ™ 9085 Aerospace ULTEM™ 1010 (PEI)	PPSF/PPSU (poly phenyl sulfone) Antero™ 800NA (PEEK) Antero™ 840CN03 Diran™ 410MF07

Fig. 6. Some modelling and functional parts produced using thermoplastic and elastomeric materials (e.g. TPU, PETG, PP, PLA and ASA) materials and extrusion-based AM (adapted from [53-56]).

3.1.1.2. Polymer composites

Most commercially available polymer composites filaments used for extrusion-based AM process are fibre- and/or particle-reinforced polymer composites [57], commonly used for aerospace, automotive, electronics and biomedical applications. Theoretically, polymer-matrix composites form a class of material systems that can comprise of various configurations such as are listed as follows:

- Petrol and bio-based polymer blends (binary, ternary, etc.);
- Fibre/sheet-reinforced polymer composites;
- Fibre/sheet-reinforced polymer bio composites;
- Fibre/particle-reinforced polymer composites;

- Fibre/particle-reinforced polymer bio composites;
- Fibre/particle/sheet-reinforced polymer composites;
- Fibre/particle/sheet-reinforced polymer bio composites;
- Hydrogels (water/gel + water absorbent polymeric network), hydrogel composites, polymer-based pastes, and polymer and biopolymer-based inks.

The identified polymeric configurations highlight potential benefits for eco-sustainability and multifunctionality in the development of advanced, SMART (specific, measurable, achievable, realistic, and time-bound) and bio-material systems. Although blends and reinforced polymer composites provide more functional properties, these AM materials can be limited in their applications as feedstock for extrusion-based AM. This is due to the potential variety of flow (rheological) and thermo-mechanical behaviour expected from different material system formulations during feeding, deposition and part formation [46, 48, 58]. This specific feature therefore presents the challenge of tailoring each material system formulation and processing limits for effective extrusion-based AM. Nevertheless, there have been some major developments in the printing of continuous fibre reinforced thermoplastics using the setups shown in Fig. 7.
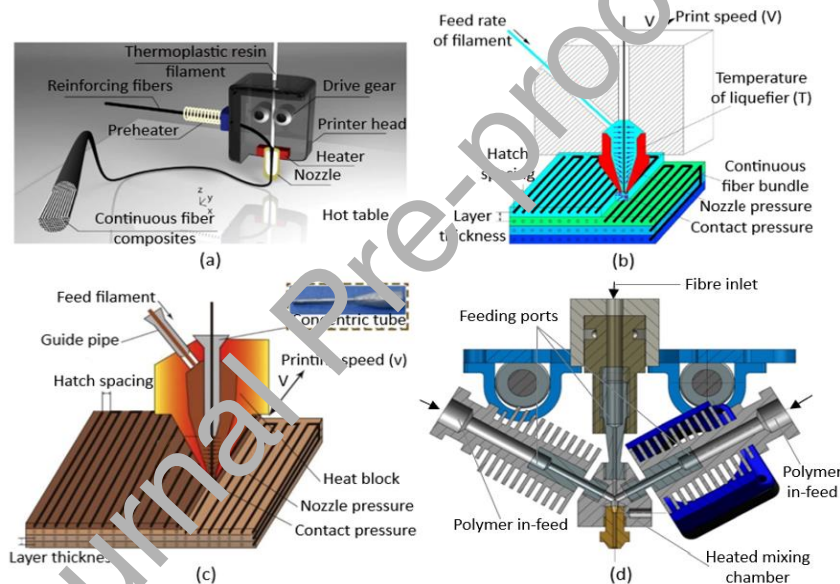

Fig. 7. Current extrusion-based AM machine setup for fabrication of polymer composite parts: (a) Namiki et al. [59]; (b) Tian et al. [60]; (c) Ye et al. [61]; (d) Prüß and Vietor [62] (adapted with permission from Ref. [63]).

By using setups including those depicted in Fig. 7, carbon and glass-fibre reinforced AM materials for extrusion-based AM processes can be used to deliver parts and components as given in Fig. 8. These setups can allow users to print desired parts either by using a preformed short-fibre reinforced polymer composite filament/pellet, or by simultaneously feeding and extruding polymers and reinforcement materials in order to obtain a fibre-reinforced polymer composite part. Recently, the DLR Institute of Composites Structure and Adaptive Systems, Germany has been involved in developing a novel low-cost process for the impregnation of multi-length fibre-reinforced thermoplastic composites using a 19.5 kHz sonotrode [64]. Such a low-cost process development can enable a scalable level of production for short, mixed and continuous fibre reinforced composites of ABS, PLA and nylon, while driving the research and development of fibre/particle-reinforced polymer composite processing for extrusion-based AM technology. AM machine and filament manufacturers including Stratasys, Markforged, and Ultimaker have been able to

commercially provide various short/continuous carbon fibre-reinforced thermoplastic filaments for extrusion-based AM applications in a broad range of industries. This capability can be attributed to the presence of a growing market that considers reinforced polymer composites a relatively easier material to use for extrusion-based AM.

Fig. 8. Continuous carbon-fibre reinforced thermoplastic composites printed using an FDM extrusion-based AM process [63].

3.1.1.3. Metal/metal-alloy composites

The state of the art in extrusion-based AM of metals and metal alloys involves the use of metal-filled filaments (i.e. filaments made of fine particles of the desired metal or alloy in a polymeric matrix) [65, 66]. Some of the metals and alloys in use includes copper, bronze, brass, and stainless steel, which require a high percentage of metallic particle/powder added to the resulting filament. Hence, the metal-filled filaments tend to be abrasive when passing through sections of the AM machine and can lead to equipment deterioration and eventual damage. This problem can be mitigated by using harder grade materials for the internal geometry of key sections of the print head, which would effectively increase machine reliability and reduces production downtimes in the expense of process and production cost; particularly when considering low-volume production runs.

Recently, Markforged developed their own method for printing metal parts using extrusion-based AM; known as bound powder extrusion (BPE). This approach for extrusion-based AM uses injection-moulding grade metal and metal-alloy particles (embedded in a waxy polymeric binder) to print desired parts resulting in a green part that requires subsequent washing (de-binding) and sintering steps, amongst other relevant post-processing steps, through which a functional or multifunctional parts are obtained [67]. Hence, for a robust part with limited voids, low shrinkage, and high green density; high metallic-particle contents are favourable especially for the purpose of consolidating any part shrinkage that occurs during the sintering and post-processing steps [67, 68]. With the fabricated production parts shown in Fig. 9 [67, 69, 70], on the left-hand side, a replica of a watch case from Vortic Watches Co. is shown, printed with stainless steel (17-4PH), while other inserts show prints of similar stainless-steel grade (post-processed) and bulk metallic glass materials. The potential shown by these prints extend to the use of bound ceramics and ceramic-composites materials in extrusion-based AM processes, and ultimately to the advancement of reliable and functional resource materials for extrusion-based AM. Additionally, it is useful to know that there are metal-looking filaments in the market which have metallic colouring added to the filament. These filaments do not contain any actual metal powder, and therefore lack the functional properties

of metal-filled filaments; further making these filaments as easy to print as pure thermoplastic or elastomeric filaments.

Fig. 9. Functional printed components fabricated using extrusion-based AM of metal/metal-composites using: (a) 17-4PH stainless steel, (b) 17-4PH stainless steel (post-processed), and (c) bulk metallic glass (BMG) (adapted from Refs. [67, 69, 70]).

3.1.1.4. Hydrogels & bio inks

Hydrogels are 3D network of crosslinked polymers (either natural or synthetic) with the ability to absorb and retain large amounts of water. This capability makes hydrogels a highly tuneable and versatile class of polymer materials that have gained a wide-reaching application in tissue engineering, regenerative medicine, waste water treatment and soft robotics [71]. Hydrogels and bio inks amongst other advanced materials offer self-healing, self-actuating, self-sensing, shape-shifting and/or self-diagnostic properties that can contribute to the development of smart (specific, measurable, achievable, relevant and time-bound) parts and products. This group of advanced materials show a unique capability of delivering stimuli-dependent properties that are predictable and repeatable. The field of smart materials; mainly including piezoelectric polymers (dominated by fluoropolymers and their composites) have gained significant interest due to their flexibility, biocompatibility, lightweight, toughness, high energy conversion rate, chemical and thermal stability [72]. Most traditional techniques used in the fabrication of such materials are semiconductor-based and involve solution casting fabrication techniques, both of which are labour-intensive, expensive and time-consuming, hence driving developments of alternative fabrication methods like extrusion-based AM process. In this regard, the application of hydrogels in extrusion-based AM is still a very new concept that makes it a relatively challenging class of materials for printing useful SMART/biomaterial parts. This is due to challenges in achieving reliable material control for accurate printing and functional part production [73]. For the nature of hydrogels and bio inks, the concept of DIW is the preferred option used for extrusion-based AM. Fig. 10 [74] shows the use of a bio ink made of protein cells, silicone and silver nanoparticles - for the fabrication of a bionic ear used for further research and development activities.
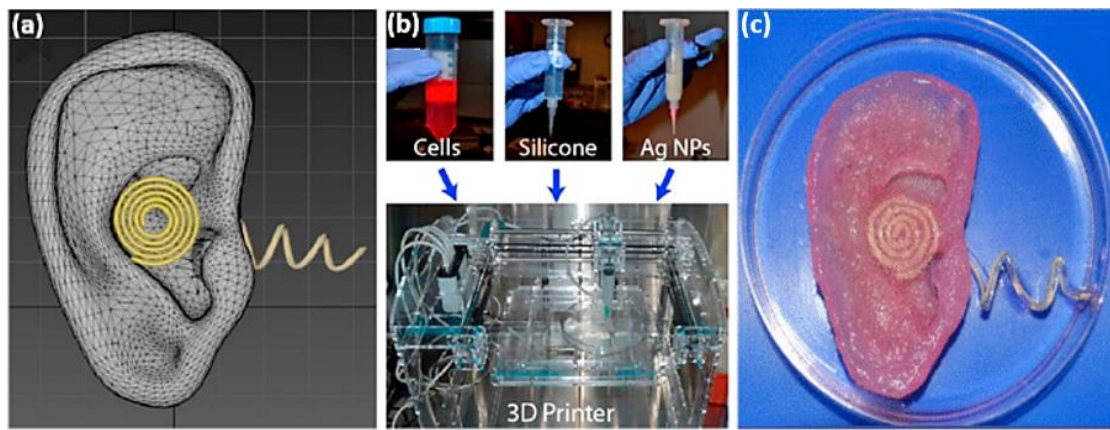
Fig. 10. (a) 3D CAD model, (b) multimaterials system, and (c) printed version of the 3D bionic ear (reprinted with permission from Ref. [74]).

There are significant research gaps to be filled for piezoelectric materials to become one of the promising extrusion-based AM materials, and more research is needed to facilitate working with a variety of piezo electrics beyond poly vinylidene fluoride (PVDF) and shape memory polymers like TPU that are used in bio ink and hydrogel-based material applications [71]. Furthermore, there are also critical challenges that include: limited extrusion-based printing simulation models, limited range of material options, and lack of standardized methods used in generating engineering data from the functional testing of printed samples [72]. Nevertheless, the development of advanced materials for extrusion-based AM process is promising due to the potential for using hydrogels and polymer composites in either of FDM/FFF or DIW extrusion-based AM processes, thereby creating great areas for exploration in terms of material property control and 3DP strategies.

3.1.2. Concrete mixtures

The AM of concrete parts, also known as 3D concrete printing (3DCP), was developed over the past five decades, and is recently capable of achieving ultra-high strength (100 - 200 MPa) concretes [75]. Consequently, considering that about 10 billion tons of concrete are produced annually [76], it shows that material property developments in cements and other ceramic-/construction-based mixtures can lead to the realisation of advanced construction strategies (via extrusion-based AM process) for highly impactful eco-sustainable construction projects. Natural and synthetic biomaterials make up existing and potential material solutions for advanced and eco-sustainable ceramic and concrete mixtures. Some examples of biomaterials are proteins (polysaccharides, starch, etc.), clay, water, sand, metals, wood, lignin, cellulose, carbon-based materials like graphene and carbon-nanotubes, and composites [77, 78]. These materials are generally considered for use in the formulation of ceramic composites (i.e. bio-inks, pastes, slurry, cement, hydrogels, and biopolymer composites) for the design of eco-sustainable and high performing ceramic- and concrete-based materials that are applicable in extrusion-based AM process [76]. The concept of 3DCP is theoretically similar to that of DIW, hence requiring less thermal input compared to FDM/FFF extrusion-based AM processes [76]. According to the fabrication activities highlighted in Fig. 11 [79], concrete structures can be created relatively easily using extrusion-based AM; and can be used for cost-effective domestic building constructions with the use of reinforcements especially in some parts of the world where temporary and on-demand homes are required to support the victims of environmental disasters, and people with low income.
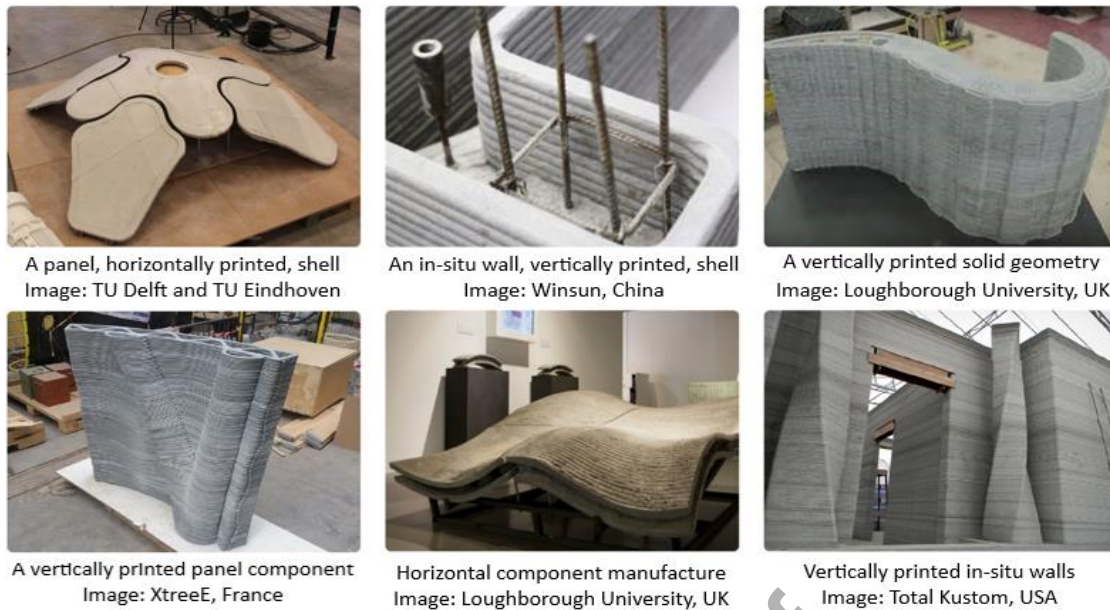
Fig. 11. Concrete structures produced by different groups using extrusion-based AM (reprinted with permission from Ref. [79])

3.2. Hard-to-print additive manufacturing materials

3.2.1. Polymer thermosets and thermoset composites

Thermosets are amorphous polymers with highly cross-linked microstructures. Thermosets cannot generally be remelted or re-liquified once these AM materials have been cured and formed into a structure; a property that limits their recyclability. However, with the development of vitrimers in 2011 [80, 81], these thermosets with adaptable and reversible covalent molecular networks have changed the perspective on thermoset processability and recyclability. Nevertheless, for traditional thermosets, factors including curing time and level of structural retention post-printing significantly create challenging conditions that make thermosets a harder class of polymers/materials to use in extrusion-based AM processes. However, the DIW extrusion-based AM process theoretically offers better compatibility (than FDM or FFF techniques) for using thermosets, mainly because constituting prepolymer thermoset materials can be premixed and printed or printed and cured on site to form the desired part. This approach can be facilitated by similar setups to those shown for continuous fibre-reinforced thermoplastic-based composites, with further support provided by light or thermal-activation processes [82]. Nevertheless, the optimism with DIW process for thermosets (and vitrimers) surrounds the control of curing rate and part formation integrity as critical factors for realisation of near-net-shape, functional thermoset and thermoset composite parts produced by extrusion-based AM processes. More promisingly, a method known as additive freeform molding, utilising the benefits of extrusion-based AM and casting, has been developed by Fraunhofer Institute of Manufacturing Engineering IPA to facilitate the use of thermosets in 3D printing applications. In an example of such development, the composite manufacturers, Magnum Venus Products (MVP) have developed a medium/large-scale thermoset 3D printer in collaboration with the Oak Ridge National Laboratory in Tennessee, USA [83]. These developments, although indicative of exciting potential, lack broadly established techniques and strategies for repeatable and reliable extrusion-based AM of thermosets, thereby making it still one of the harder materials to print amongst widely used AM materials.

3.2.2. Matrix (metal, glass, and ceramic)-only materials

Standalone solid metal, glass and ceramic-matrix materials cannot directly be used in extrusion-based AM processes such as FDM, FFF and DIW [84]. Theoretically, the processing of these materials requires print heads and build platforms with extremely high thermal stability and abrasion resistance, which inherently leads to a high-cost manufacturing technology that may also possesses significant health and safety hazards during operation. Nonetheless, the challenging recrystallisation or solidification dynamics of metals and ceramics respectively creates another challenge for processability and inter-bead/inter-layer bonding, particularly because the extruded material and build volume need to maintain complex temperature profiles to facilitate effective deposition, high bonding level of printed layers, and enhanced part accuracy. These requirements make standalone metals, metal-matrix composites, ceramics, and ceramic-matrix composites one of the hardest materials to print using extrusion-based AM technologies. Interestingly, such findings are understood to be driving the development of composite material systems that incorporate high contents of metals and/or ceramics-based materials for their utilisation in extrusion-based AM.

3.3. Widely used extrusion-based additive manufacturing processes

There are various types of extrusion-based AM process developed following the expiration of patent of FDM which was invented by, the co-founder of Stratasys Ltd., Crump [45]. This technique was initially capable of only processing two types of printing-friendly polymers i.e. ABS and PLA. However, variety of AM materials can currently be fabricated using FDM (including metallic materials, composites, multimaterials, ceramics, construction materials, food materials, several types of polymers, and biomaterials) thanks to the recent advancements in the AM technology and material science [85]. As a slightly modified version of FDM, FFF does not involve an enclosed building chamber as mentioned in Section 2.2.1, which makes FFF more economic fabrication technique for the variety of AM material that can be also printed using FDM. In this regard, desired parts produced by FFF shows lower mechanical properties e.g. higher bonding strength and dimensional accuracy than those of parts produced by FDM. Because of this feature of FFF, achieving a high dimensional accuracy of parts without experiencing any defect caused by the temperature difference between deposited AM material and environment is highly challenging. In FFF, particularly glasses and some metals having high solidification ranges experience detrimental hot cracking and shrinkage during the thermomechanical cycle (liquefaction-deposition-solidification) of AM materials during the fabrication, which impairs the bonding quality of successively deposited layers and bonding quality [32]. Another widely used extrusion-based AM is DIW that AM materials in this technique are normally in the form of soft pastes or liquid inks. The desired parts can be fabricated even at low printing temperatures around RT, which makes DIW a highly suitable option for the 3D printing of heat-sensitive AM materials such as biomaterials, some food materials and photopolymers. In the mechanism of DIW, the curing via chemical bonding between successively deposited layers is achieved by interlayer cross-linking, and UV rays and microwaves can be also used to assist the curing process [86]. Therefore, DIW does not involve the melting of raw AM materials in contrast to FDM and FFF. Material options to be processed by DIW are ceramics in paste form, photopolymers (including heat-sensitive photopolymers), glasses, silicones, food materials (e.g. mass production of cheese and chocolate in robotic-arm-included fabrications), biomaterials including ceramics or ceramic-based composite biomaterials (biodegradable and biocompatible materials as inks), smart material (e.g. smart textile products), and celluloses in ink form. In addition to these popular extrusion-based AM processes i.e. FDM, FFF

and DIW, there are other specific types of extrusion-based AM processes as compared in Table 3 that are developed to process some specific AM materials. For instance, the materials option for robocasting is limited to ceramics and bioceramics, and metals, and this process can characteristically not be associated with the drying or solidification of deposited AM materials [87]. Rest of the extrusion-based AM processes [88-98] such as 3D concrete printing, composite filament fabrication, ceramic on-demands extrusion and bioprinting are only capable of processing cementitious materials, composites, ceramics and biological materials (e.g. human tissues and cells) respectively [8].

Table 3. Comparison of widely used extrusion-based AM processes.

Extrusion mechanism	Extrusion-based AM process	Suitable materials	Typical building volume (m^3)
Filament-Based	Fused deposition modelling (FDM)	Ceramics, polymers, chocolate, cheese	0.51 [88]
	Fused filament fabrication (FFF)	Polymers, bioceramics, metals	0.79 [89]
	Fused deposition of ceramics (FDC)	Ceramics	0.016 [90]
	Composite filament fabrication (CFF)	Composites	0.007 [91]
	Fused layer modelling (FLM)	Polymers, food materials, ceramics	0.0062 [92]
	Fused granular fabrication (FGF) (Pellet printing)	Plastics, composites	1.01 [93]
Plunger (Syringe)-Based	Fused filament fabrication (FFF)	Polymers, bioceramics, metals	0.01 [94]
	Direct ink writing (DIW)	Celluloses, biomaterials	0.015 [95]
	Robocasting	Metals, ceramics	0.01 [96]
	3D concrete printing	Cementitious materials	Depending on the size of gantry or robotic arms
Screw-Based	Fused deposition modelling (FDM)	Ceramics, polymers, chocolate, cheese	0.048 [97]
	Melt extrusion manufacturing (MEM)	Biomaterials, biopolymers	0.01 [98]

4. Suitability Analysis of Extrusion-Based Additive Manufacturing: Materials and Processes

Suitability analysis can broadly be defined as the determination of suitability of any base input, e.g. process, method or material, considering to what extent the input meets the requirements, and output demands [99]. In this section, the suitability analysis has been adopted for extrusion-based AM materials and processes to help determine whether an extrusion-based AM material or process is suitable for their intended application and outcome. To give a better idea of the sort of context to be discussed, the suitability of powder-based AM materials and processes is highly dependent on the powder characteristics e.g. shape, distribution, size, and chemical composition of powder particles being used [36]. Such suitability analysis for powder-based AM processes has been conducted in several studies. Some of the examples includes works done by Mauduit et al. [100], in which the suitability of several aluminium alloys (AA2017, AA2219, AA6061, AA7020 and AA7075) was

investigated for the powder bed fusion (PBF) AM process, for which they considered the effects of laser scanning technique on crack formation. Fixter et al. [101] also conducted a suitability analysis to investigate the suitability of AA2024 for wire arc additive manufacturing (WAAM), and successfully showed the suitability of WAAM to produce large Al alloy aerospace components. Evidently, such suitability analysis, has however not been conducted for extrusion-based AM materials and processes in the literature yet – especially as the main focus of academic papers. Therefore, in the following subsections (i.e. Section 4.1 and Section 4.2), we focused on the material- and process-centred suitability of AM materials and extrusion-based AM processes as a means to close this gap in the literature.

4.1. Suitability of additive manufacturing materials

The extent of material consideration for extrusion-based AM should be broad and especially inclusive of advanced materials as these may realise significant improvements in the realisation of multifunctional and sustainable part properties. Consequently, the materials considered for a suitability analysis with respect to extrusion-based AM may include polymers (thermoplastics, thermosets and elastomers), polymer-matrix composites, metals, metal alloys, metal-matrix composites, hydrogels, bio inks, ceramics (concrete & concrete mixtures like mortar), and ceramic-matrix composites, in an attempt to be exhaustive. This suitability analysis covers factors surrounding the preparation, handling, processability (i.e. response to general processing conditions), and end-part property/quality (considering potential post-processability and end-part functionality). Based on this, we consider the principle for extrusion-based AM processes that can then build up to form simple to complex functional constructs. These AM processes require materials that can be caused to flow controllably and supporting the layer-by-layer deposition of extruded material beads. Essentially, the chosen material system needs the physical properties to maintain its deposited position and form, while achieving sufficient interlayer interaction and bonding that would ultimately yield a more accurate, robust and reliable end-part [102, 103]. Furthermore, achieving the consistency required for industrial and commercial adoption further depends on supplier quality, process control and monitoring capabilities. To understand the essential property requirements for heat and pressure-assisted extrusion-based AM materials, refer to Fig. 12 for the relevant and fundamental material properties, because the consideration on these material properties is necessary for intended applications.
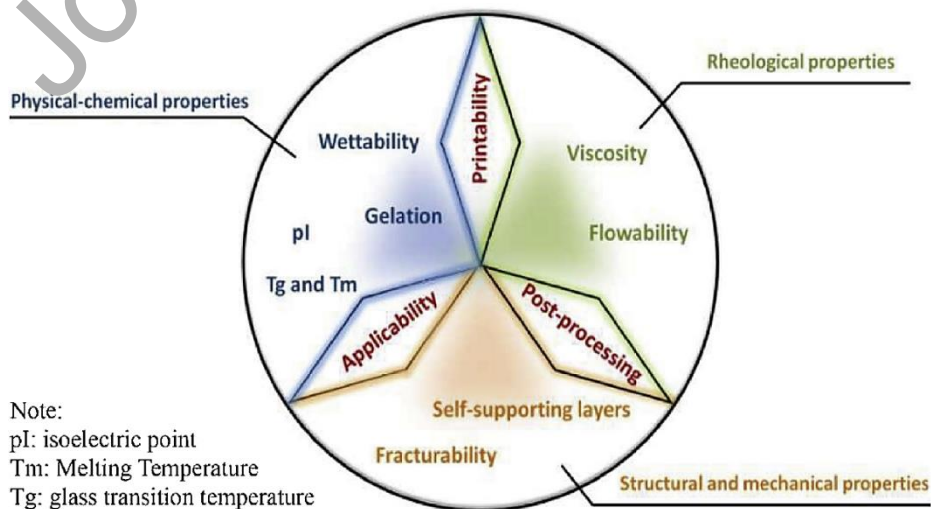

Fig. 12. Material properties to consider upon extrusion-based AM of structures and parts (reprinted with

permission from Ref. [102]).

4.1.1. Heat-assisted materials for extrusion-based additive manufacturing

Heat-assisted extrusion-based AM materials can be thought to comprise of polymeric material systems that have inherently stronger intermolecular bonds and therefore require a relatively higher endothermic reaction to weaken bonds and cause sufficient material flow for extrusion processes [104]. Thermoplastics and their composites are among the most processable materials for extrusion-based AM. However, their suitability in extrusion-only processing (i.e. material transport and extrusion printing), which in some cases is limited for highly semi-crystalline materials [105], does not necessarily cover their suitability for other stages of the AM process like post-processing, quality control, and storage. Popular heat-assisted extrusion-based AM materials tend to have a relatively broad thermal processing windows and higher thermal stability that allow them to critically withstand the thermodynamic cycles experienced during the processing lifecycle of materials (i.e. leading up to final print and part production). Particularly, the capability of PP, PLA and PLA-based composites have been investigated for hot-melt extrusion processing [105-107]. These studies often include physicochemical and rheological characterisations that aim to identify correlations with 3D-printability, post-processability, and end-part properties (or applicability) – as shown in Fig. 12. Hence, the suitability of polymer-based materials can be strongly considered to depend on factors such as the melting, crystallisation, wetting, and rheological properties exhibited by the material throughout the thermal cycles involved in filament/pellet processing and extrusion-printing stages. These factors are therefore of critical significance in the development of heat-assisted composite materials for extrusion-based AM, mainly because composites introduce complex multi-material considerations for their use in manufacturing processes.

4.1.2. Pressure-assisted materials for extrusion-based additive manufacturing

Syringes, micro-syringes, pumps and such devices implemented for material deposition are some of the main tools and equipment used for pressure-assisted material processing in extrusion-based AM. Suitable materials for this type of extrusion-based technology must be capable of controllable flow in response to a pressure-driven extruder. Consequently, pressure-assisted AM materials are typically materials expected to have uniquely different physical properties from those of heat-assisted AM materials. Particularly, the former tends to have lower viscosities than the latter at any given temperature [58, 71, 108], and hence the reason for little or no thermal input in their extrusion and printing processes. Nonetheless, just as in heat-assisted materials, the processed pressure-assisted AM materials need to have suitable properties that enable extruded beads and layers that retain their form and position while also realising good interlayer bonds that results in final prints that are processable for quality control, post-processing, storage, functionality and end-of-life processing. Cementous mixtures, geopolymer composites, and pharmaceutical formulations (including hydrogels, thermosetting components, bio inks, pastes, etc.) make up the sort of materials that meet the requirements of pressure-assisted AM materials [58, 71, 108-110] as opposed to the traditional heat-assisted amorphous/semi-crystalline polymers currently dominating most extrusion-based AM processes. So far, flocculation and nucleation activities have been identified as key properties of cementitious mixtures that enables sufficient storage modulus and interlayer molecular interactions as prerequisites for successful printing and robust part formation respectively [108]. Consequently, this suggests that extrusion-based 3D printing of materials requires juggling between micro and macro-physical properties and printing-process conditions for the realisation of accurate

and reliable 3D printed geometries. Fig. 13 shows viscosity values of some common substances, and the controlling properties that determines the requirement for a more pressure or heat assisted extrusion-based AM process.
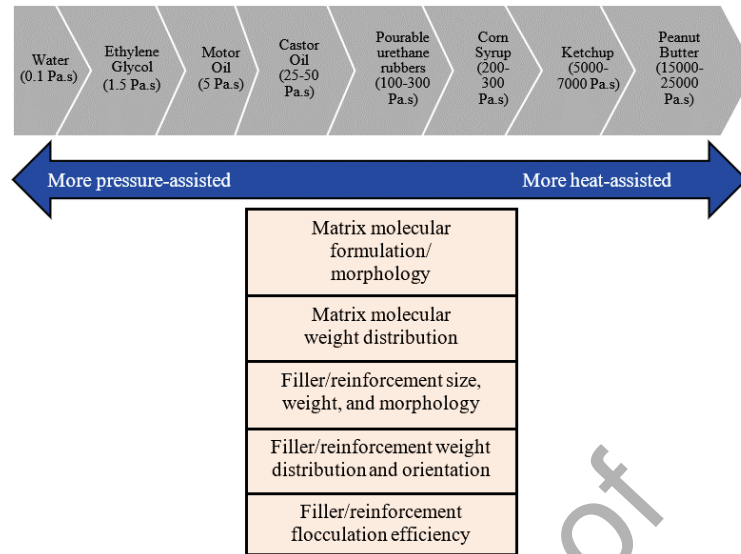

Fig. 13. Viscosity of common materials (above), and controlling factors that determine material use in either more pressure or more heat-assisted extrusion-based AM processing (below).

4.2. Suitability of extrusion-based additive manufacturing process

Extrusion-based AM processes are recently being developed to cover a variety of materials and processing requirements necessary for realising advanced multifunctional material and product systems. Although FDM, FFF and DIW led the way so far, their associated process developments like robocasting, 3D concrete printing (3DCP), composite filament fabrication (CFF), and ceramic on-demand extrusion (CODE) are further expanding the potential of extrusion-based AM [8]. In this section, the suitability of extrusion-based AM technologies was assessed according to the factors in Table 4.

Table 4. Factors considered for suitability analysis of extrusion-based AM process.

Suitability Factor	Description
Safety and risk evaluation	Hazardous concerns with the material resource, extrusion-based AM machine components, and processing steps involved
Ease of scalability	Limitations to the scale of printable parts, mainly due to extrusion-based AM machine components and setup
Machine (operating) cost	Cost of obtaining and running extrusion-based AM machine components
	Additional cost of maintaining innovative extrusion-based AM components
Environmental applicability	Feasibility of carrying out extrusion-based AM activities in specific environments using specified setups
Printability and complexity of process	Capability of printing of AM materials, and components of extrusion-based AM process
Material option and availability	Scale of the wideness of AM materials that can be printed
Post-processing and printing accuracy	Last stage needs to be applied on printed parts or any task to be applied to further enhance the properties of parts. Consideration on how close the measurement of printed parts close to their true values

4.2.1. Safety and risk evaluation

Popular FDM- and FFF-based 3D printers like the Flashforge Creator Pro 3D, Ultimaker S5, and Creality Ender 3 (Fig. 14 [111-113]) generally use an electrical input rating of 100~240 V AC, 50/60 Hz, with printing temperature, bed temperature, and printing speed of ≤ 280°C, ≤ 120°C, and 20~150 mm/s respectively. Furthermore, as we reflect on the use of materials based on ABS, PLA, and nylon, it was found that extrusion-based AM activities have the potential to expose its users to ultrafine particles (UFP) and volatile organic compounds (VOCs) due to the influence of extruder nozzle temperature, printer bed temperature, print speed, nozzle diameter, and machine design (i.e. open or enclosed systems) [114].

(a) (b) (c)

Fig. 14. Popular FDM- and FFF-based 3D printers in the market, with open and enclosed systems: (a) Creality Ender 3 (credit: Creality Ender) [111], (b) Ultimaker S5 (credit: Ultimaker) [112], and (c) Flashforge Creator Pro 3D (credit: Flashforge) [113].

Although the choice (and chemical composition) of filament material plays a fundamental role in determining the level (and type) of emissions, the nozzle temperature is a critical factor for determining the level of UFP emission [115, 116]. Among prominent extrusion-based AM materials, PLA has been found to be a low-emitting, and one of the safest material options for FDM- and FFF-based 3D printers. However, Wojtyla et. al. [117] found that ABS, the most widely researched polymeric material option, released styrene during printing, while other researchers [118-121] further reported their findings reporting that indicate toxic effects of ABS upon extended workplace exposure. In another material case, Bernatikova et al. [122] evaluated the UFP and VOC emissions of PETG and co-polyester filaments using an enclosed printer, and reported potentially harmful particle emission rates, although at a low level. These findings, although based on closed-design FDM and FFF 3DP machines, more importantly highlights the safety concerns and risks associated with using open-design FDM and FFF 3DP machines, like the Creality Ender 3, and other developing open-design techniques (e.g. CODE and 3DCP – seen in Fig. 15) [123, 124]. Such concerns are therefore heightened when considering the use of multiple 3DP machine setups in a shop floor or industrial production environment. However, possible solutions could involve material design optimisation, operator management, process replanning, strategic filter positioning (e.g. around nozzles, and regions with high risk of UFP and VOC emissions).
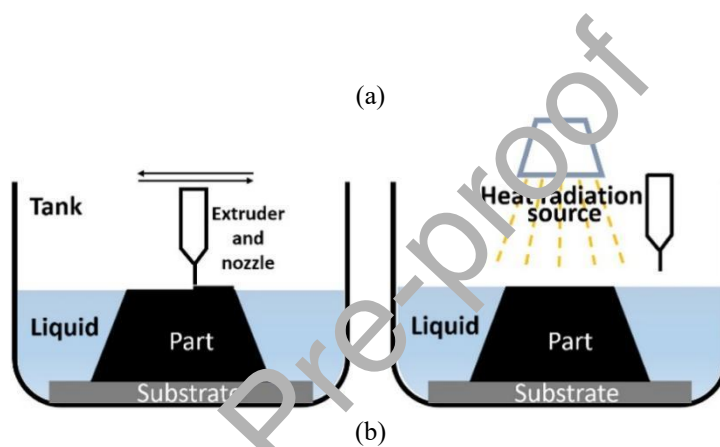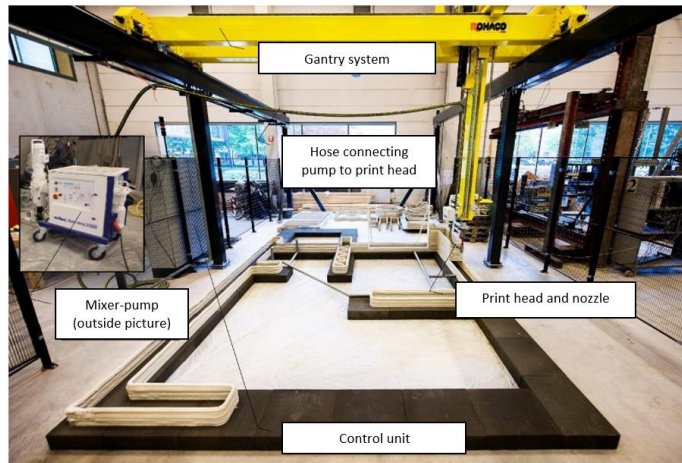
(a)

(b)

Fig. 15. Illustrations of (a) 3D concrete printing (3DCP) system [123], and (b) ceramic on-demand extrusion (CODE) process showing extrusion and curing steps (using heat radiation) [124]; both in an open-design system.

4.2.2. Scalability (building volume)

The scalability of an extrusion-based AM method is strongly dependent on the design of the system (open or closed), and additionally on the print bed size. In most cases, FDM and FFF printers are either closed or open 3DP machines, with fixed maximum building volume, typically around 400×400×300 mm. Relevant developments for FDM- and FFF-based 3DP machines involve an infinite (continuous) axis 3D printing machine (Fig. 16(a)), which allows parts to be printed and conveyed to the next process or into a part collection unit (Fig. 16(b)). The conveyor-style 3D printers offer a production process that minimizes production downtime and infinitely enhances build length, while increasing print size and volume, hence allowing for a good level of scalability. The Creality CR-30 is among the most cost-effective conveyor-type 3D printers in the market, retailing at around $800~$1000 [125, 126]. Meanwhile for industrial grade applications, Blackbelt 3D offers conveyer-type 3D printers worth around $10000 [126]. Other opportunities for scalability are offered by 3D printers fitted with a SCARA type print-head coordinate systems [127]. These are the sort of printers used in the construction industry and cost upwards of $10000. They offer better flexibility and allow for control using robotic arms, and enables longer dimensional prints in all axes, rather than in only one, as is offered by conveyor-style 3D printers.
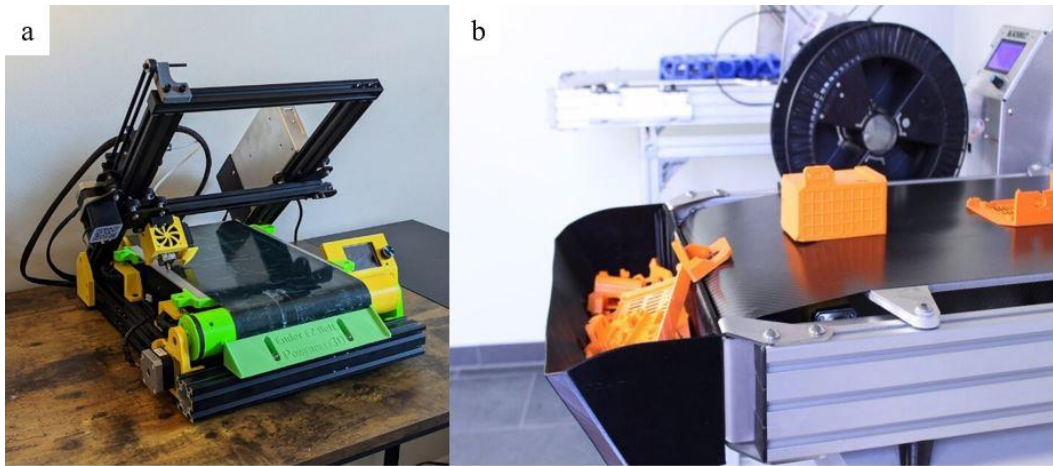
Fig. 16. Representations of (a) Conveyor 3D Printer (credit: Powerbelt3D) [128], and (b) Conveyor 3D printer conveying printed parts into a collection unit [129] to allow for continuous printing, and thereby eliminating stops usually used for part removal and printing restarts.

4.2.3. Machine (operating) cost

Extrusion-based AM machines (using standard FDM and FFF processes) currently dominate the AM market, and the following costs tend to apply for FDM- and FFF-based 3D printers within each category below [129]:

- DIY/Low-cost 3D printers ($150 ~ $400);
- Hobbyist 3D printers ($400 ~ $1000);
- Enthusiast 3D printers ($1000 ~ $2000);
- Professional 3D printers ($2000 ~ $10000);
- Industrial/Large-format professional 3D printers ($4000 ~ >$10000).

Based on the machine costs given above, it can be inferred that the total machine cost of any extrusion-based AM process is mainly linked to scalability, part quality and printing speed. It also implies that the operating (running and maintenance) cost may be considerable for the more professional and large type 3D printers. However, this may be offset by the effect of "economies of scale" associated with using such machines for higher volume or higher value production runs. In the case of CFF for example, the addition of reinforcing components (e.g. fibres or particles) increases the cost by a factor of 2-3*x* (in the case of PETG vs PETG/20 wt% CF – see Table 5) but allows for better quality parts to be produced. Table 5 shows the cost of filaments on the market (as supplied by RS Pro and Amazon) [130, 131].

Table 5. Current market prices (£/Kg, unless stated otherwise) of popular filament materials (CF = carbon fibre) [130, 131].

Filament material	Retailer/vendor online price (£/Kg)	
	RS Pro (excluding VAT)	Amazon
HIPS	34.79	29.08
PLA	27.70 ~ 28.66	13.99 ~ 22.99
PETG (20 wt% CF)	30.92 (per 500 g)	32.99
ABS	27.57	11.99
TPU 95A	41.93 (for 750 g)	22.99
MT-Copper	62.10 (per 750 g)	–
PETG	22.41 (per 500 g)	13.99
PA	57.87 (per 800 g)	28.59
PLA (20 wt% CF)	–	29.99
PA-CF	–	45.99
ABS (20 wt% CF)	–	51.44

The prices listed in Table 5 show that Amazon has the cheapest filament prices amongst the two companies; however, support services from Amazon (and partners) may not match that of RS Pro in unique aspects. Furthermore, prices of carbon fibre-reinforced polymers can be up to 4.3x more (at 20 wt% of fibre content). Interesting, as applications start to require varying carbon fibre loading, manufacturers can incorporate sufficient cost savings (through tailored product and production design), and that will help sustain the venture. Therefore, considering this relevant aspect, software like AutoCAD, Solidworks and NX contribute to the design for manufacturing (DfM) of a 3DP process. Cura, for example, offers a model processing (conversion process from STL to G-code) software that can be downloaded for free, although this is not the case for all 3DP software. Nonetheless, with lower requirements, total software cost can usually be kept low, although further requirements for data security and other software services can lead to increased software cost contribution. At this point, consider a 3DP job of a given period, and for which the energy utilisation can be measured to help identify the energy footprint generated by the process. This information, together with the cost of material utilized (for printing), software cost, personnel cost, and machine cost (including maintenance and part replacement cost), can be used to calculate an estimate of the total cost of a given 3DP project. Importantly, assuming the costs of electricity, machine, and software remains the same, perhaps for a set of batch production runs, then the cost of filament material quickly comes across as the most likely component to influence the production cost, particularly in the case of suboptimal product or process design activities. Nonetheless, the reusing or recycling of filaments can help counter potential increases in the cost.

4.2.4. Environmental applicability

Environmental applicability refers to the conditions of the environment for which the extrusion-based AM technology can be applied, as well as the safety of the process or the environment of operation. The conditions for extrusion-based 3DP, especially in open systems, need to consider the pressure and temperature conditions of the surrounding environment, as certain 3DP systems or materials may face challenges in completing print jobs efficiently and effectively in certain conditions. Perhaps, this is where closed system (FDM or FFF) 3D printers come in, however, with limits on scalability. Consequently, the correct use of certain extrusion-based 3DP technologies in places like schools, hospitals, construction sites, laboratories, etc., form the basis for the consideration of ''environmental applicability'' as a factor constituting their suitability for

extrusion-based AM. Typically, the most widely used type of extrusion-based AM technology (FDM or FFF) may be considered best in most cases, as it can usually be used in a variety of environmental settings, which includes schools, hospitals, laboratories, and workshops, amongst others. Such technologies usually involve the use of closed-system or robotic-assisted extrusion printing machines, as they offer safe (cost-effective) and limitedly scalable (high-value) 3DP processes respectively. Nonetheless, it may be useful to further consider the reliability of 3DP machine parts and printing filament materials upon exposure to certain challenging environmental conditions over a period of time (e.g. acidic, high pressure, humid, rainy, or combination of these).

4.2.5. Printability and process complexity

The printability and process complexity of an extrusion-based AM process comes down to the conditional requirements that allows for effective processing of a material resource so that it delivers accurate and reliable deposition, which further leads to effective interlayer and inter-bead interactions that ultimately deliver an accurate and robust final part (i.e. following any post-processing steps). Consequently, the software applications, material infeed units, nozzles, nozzle designs, gantry systems, thermobaric (or other physical or chemical) controls, support structure design, and post-processing steps can contribute to the complexity of an extrusion-based AM process. For example, in the CODE method of extrusion-based AM (Fig. 15), a heat radiation source is used to facilitate the process. In another case, the use of a large sized gantry for 3DCP brings a different type of complexity for consideration. However, printability is most fundamental, and is dependent on the rheological properties of material resources throughout the processing cycles of AM – especially in terms of the flowability, viscosity, storage/loss modulus at various temperatures and shear rate states – which control critical aspects that aid positional accuracy and the ''form retention'' of extruded beads and roads during 3DP.

4.2.6. Material option and availability

The materials used for extrusion-based AM form the largest set of suitable materials amongst all the sets of materials used within each AM process category. And although the options are many for extrusion-based AM, there can be possible limitations based on process (machine and equipment) design, which influences the level of the end-part quality. In terms of availability, the supply chain of material resources can also affect the choices of suitable materials for an extrusion-based AM project. Hence, the accessibility of such materials (in desired forms) makes up a useful factor that contributes to the overall suitability of an extrusion-based AM process. Profoundly, most commercially available materials for extrusion-based AM come as filaments; most likely due to the ease of handling and processability of filaments, which drive existing 3DP machine designs (and systems) in the market. This scenario appears to highlight some opportunities for commercial development of processing machines and equipment that are suitable for alternative material forms other than filaments and could lead to more sustainable (extrusion-based) AM process development.

4.2.7. Post-processing and printing accuracy

Post-processing is any processing of 3D printed parts after the 3D printing process is completed [132]. The post processing of 3D printed parts is crucial for achieving the desired part accuracy in terms of dimensional and functional accuracy (e.g. surface finish quality). Post-processing has been identified as either primary or secondary [133]; with primary post-processing addressing the fundamental part limitations that prevents any functional use of the part. Meanwhile, secondary post-processing addresses further enhancements to the functional part quality, beyond necessity,

with the aim of meeting greater user requirements [134, 135]. In another case, post-processing can be of a subtractive, additive, or property-enhancing approach [136]. Examples of each post processing approach are presented in Table 6 [132, 133]. Such post-processing technologies highlight the developments and adoption of unique post-processing methods that address the printing accuracy of extrusion-based AM processes.

Table 6. Post-processing approaches and examples of post-processing technologies [132, 133].

Post-processing approach	Post-processing technology		
Subtractive	Removal of support structures	Chemical dipping	CNC machining
Additive	Filling Brush coating Powder coating	Priming Dip coating	Metal plating Foiling
Property enhancing	Local melting	Vapor smoothing	Annealing

Upon careful consideration of extrusion-based AM processes and typical resolutions found in literature, the printing accuracy of the filament-, plunger-, or screw-based extrusion system is expressed as shown in Table 7. Note that although any extrusion-based AM process given in Table 7 was associated with high printing accuracy, the extrusion-based AM of some specific AM materials results in low dimensional accuracy. For instance, metallic products fabricated by extrusion-based AM normally have low printing (dimensional) accuracy than those produced by liquid- and powder-based AM processes mainly due to poor bonding of metallic layers. As another example, glasses have low dimensional accuracy mainly due to solidification cracks of these AM materials deriving from their highly brittle nature leading to detrimental crack generation after deposition. The printing accuracy of parts produced by FDM is higher than that of parts produced by FFF. The reason is because FFF is conducted in open air unlike FDM, which leads to lower level of bonding between successively printed layers and higher solidification shrinkage due to the temperature difference between the printing temperature and temperature of printing environment. DIW, after FDM, is another extrusion-based AM that is capable of printing desired parts with high dimensional accuracy. The reason behind printing parts with high printing accuracy using DIW can be attributed to: (i) the printing mechanism of DIW which does not involve any melting and solidification of AM materials, (ii) capability of operating at RT that eliminated fast solidification of deposited AM materials causing the metallurgical defects e.g. porosity and solidification cracking, and (iii) minimised temperature difference between the printing temperature (i.e. generally RT) and temperature of readily softened/liquid AM materials at around RT located inside of syringes, which eliminates the shrinkage of successively deposited layers. Therefore, the differences in between the dimensions of desired parts in their CAD files and actual dimensions of printed parts can match [137].

Table 7. Comparison of printing accuracy and typical resolution of extrusion-based AM processes.

Extrusion mechanism	Extrusion-based AM process	Printing accuracy	Typical resolution range (µm)
Filament-Based	Fused deposition modelling (FDM)	Medium to high	250 – 330 [138]
	Composite filament fabrication (CFF)	Medium	200 [139]
	Fused filament fabrication (FFF)	Medium to high	100 – 200 [140]
	Fused granular fabrication (FGF) (Pellet printing)	Low	1000 – 2000 [93]
	Fused layer modelling (FLM)	High	2.5 – 11 [92]
	Fused deposition of ceramics (FDC)	Low to medium	400 [90]
Plunger (Syringe)-Based	Robocasting	Medium	100 – 450 [11]
	Direct ink writing (DIW)	Low to high	100 – 1200 [141]
	Fused filament fabrication (FFF)	Medium to high	50 – 350 [94]
Screw-Based	Melt extrusion manufacturing (MEM)	Low to medium	200 – 500 [98]
	Fused deposition modelling (FDM)	High	100 [97]

4.3. Suitability ratings of extrusion-based additive manufacturing processes

The suitability of extrusion-based AM process, as mentioned earlier, involves multiple sub-parameters to be considered such as safety, material option and availability, machine (operating) cost, environmental applicability, and printability and complexity. The detailed suitability rating for each parameter considered is given in Table 8 - for some of the selected widely used extrusion-based AM processes listed according to their suitability ratings from highest to lowest. In the last column of the table, the overall suitability rating over one hundred can be found. In detail, FDM and DIW extrusion-based AM processes have the highest safety rating as these AM processes can be conducted in open air without necessitating any safety regulation or closed working area. Because 3DCP is associated with big-scale robotic arms, safety is one of the biggest concerns and considerations with it; thus receiving the lowest safety rating. Regarding the material option and availability parameter, FDM (ABS, PLA, and their various blends) and bioprinting (alginates, hyaluronic acid, collagens, gelatines, and synthetic polymers like polyvinyl alcohol and polyethylene glycol) AM processes currently enables the printing of various AM materials. Therefore, these two extrusion-based AM processes have the highest material options and availability rating. Regarding the printing accuracy that can be achieved using specific extrusion-based AM processes, the highest suitability ratings are received by FDM and DIW. The highest suitability ratings can be attributed to some factors related to the equipment and printing mechanisms of the two extrusion-based AM processes. The determining factors are because: (i) the dimensions of deposited layers can be highly preserved after the material deposition by FDM due to the use of enclosed building chamber effectively minimising detrimental solidification shrinkage and cracks, and (ii) in the mechanism of material deposition in DIW does not involve the melting of AM materials, which also eliminates the shrinkage and solidification-related defects. 3DCP received the lowest operating cost rating as this extrusion-based AM process involves big-scale robotic arms necessitating high maintenance cost and energy consumption. Nevertheless, 3DCP can be used in

any critical environment e.g. portable buildings, which can be printed at high volume for people who urgently need an accommodation after any natural or human-caused disaster in any harsh climate. FFF and DIW extrusion-based AM processes have the highest printability and low complexity rating because these AM processes are associated with the open area printing at relatively low printing temperatures not necessitating any complex and costly heat source to soften or melt raw AM materials being used. Overall, FDM and FFF received the highest suitability rating among all the extrusion-based AM processes covered in Table 8, whereas 3DCP has the lowest suitability rating due to the specific requirements needed and limitations with 3DCP AM process.

Table 8: Suitability ratings of widely used selected extrusion-based AM processes (in order of importance in percentage of suitability rating)

Extrusion-based AM process	Safety	Material options and availability	Low machine (operating) cost	High printing accuracy	Printability and low complexity	Environmental applicability	Suitability rating
	(0—16.6)	(0—16.6)	(0—16.6)	(0—16.6)	(0—16.6)	(0—16.6)	(0—100)
Fused filament modelling (FDM)	15	15.5	12	15	14.5	13	85/100
DIW (robocasting)	15	15	14.5	13	13	14	84.5/100
Fused filament fabrication (FFF)	13	15	14	12	13	14	81/100
Bioprinting	11	15.5	13	12	14	13	78.5/100
Robotic material extrusion	11	15	12	12.5	12.5	13	76/100
Melt extrusion manufacturing (MEM)	13	8	13	11	13	13	71/100
Composite filament fabrication	12	7	13	12	11	12	67/100
Ceramic on-demand extrusion (CODE)	11	7	14	10	11	12	65/100
Continuous fiber fabrication (CFF)	12	10	7	11	10.5	11	61.5/100
3D concrete printing (3DCP)	8	8	5	12	11	10	54/100

5. Discussion

Since the extrusion-based AM process has become widespread and demand for the customised parts produced by extrusion-based AM has increased, this technology has experienced numerous advances. However, extrusion-based AM technology is still associated with some challenges that need to be overcome to improve its suitability for sustainable and reliable adoption. As an example of process-centred issues related to the extrusion-based AM process, filament breakage occurring in the filament-based (FFF and FDM) processes forms one of the most common and critical issues

related to the extrusion-based AM process. Consequently, filament breakage in the extrusion-based AM machine leads to inconsistent extrusion or stoppage of continuous feeding of AM materials, which diminishes the suitability of the extrusion-based AM process mainly because of its negative side effects on part printability and geometric accuracy. Other process-based problems may involve the time-inefficiency associated with more complex extrusion-based AM processes like in CODE and CFF extrusion-based AM techniques. In such extrusion-based AM methods, there are alternating printing and heating steps (CODE) or alternating polymer and reinforcement printing steps (CFF) that may lead to longer print times and potentially higher costs than is suitable for certain manufacturing objectives. Hence, this creates an opportunity for improving the process design of extrusion-based AM techniques.

There are also material-centred factors limiting the suitability of extrusion-based AM technologies, which has derived from the surface roughness and mechanical properties of AM materials. As an example, the mechanism of extrusion-based AM process of metals necessitates intensive heating of these materials. Hence, the running cost for 3D printing of metals is rather costly due to intensive energy requirements and post-processing steps needed to enhance the printability and dimensional accuracy of extruded parts [142]. In order to overcome material-centred issues restricting the suitability of extrusion-based AM process, for instance, metal filaments can be composited by adding polymer fillers to the metals so that their melting point and energy requirements for processing the composite filaments are lowered without losing the key material properties of metals. Other material related-issues with extrusion-based AM involve the processing and ambient temperatures, and pressures used for extrusion-based AM. In this regard, considerations for the temperature gradients, cooling rates, and thermal conductivity of AM materials are some of the conditions that could be improved to help identify optimal processing conditions or controllable material properties that could enable better material suitability for either CFF, CODE, composite filament fabrication, and 3DCP, amongst others.

The safety of robocasting, bioprinting, composite filament fabrication, CODE, 3DCP, and CFF were considered to be least amongst the extrusion-based AM methods, especially with limited research covering their safe use in the workplace. However, safety design changes in the FDM 3D printer, especially when using volatile materials like ABS, may benefit from improved housing and filter systems that vent into an open environment or into a unit that utilizes the particulates. Nonetheless, a preferred solution would involve developing material systems that are less volatile and harmful to the user. Based on the literature, studies on the particulate emissions of most materials are lacking and would be required to catch up if at all more materials can be confidently considered safe for scalable use. In another extrusion-based AM method, i.e. 3DCP, which utilizes huge machinery and equipment, was considered to pose significant hazard to the users than most other extrusion-based AM technologies. The electrical parts, concrete material composition and moving electromechanical units of the 3DCP system were considered to be of most concern. Consequently, the thought solution for addressing the issue may involve optimising the design of 3DCP machines into machineries that use computer vision, sensors and feedback control systems to offer more safety measures for the user, although leading to increased total production cost. Furthermore, challenges with 3DCP materials can be improved by material research and development strategies, meticulous risk and control of substances hazardous to health (COSHH) assessments, and effective training and use of protective personal equipment (PPE) to mitigate potential hazards.

Machine (operating) cost appears to be a promising condition for suitability except in the case of 3DCP and CFF. In the former, very large machinery or equipment makes it expensive, while for the latter, the energy required to heat the fibre creates a source of increased cost. For 3DCP, a potential solution may involve a review of the machine design, to identify opportunities for cost reduction. Meanwhile, in the case of CFF, the selection and design of fibre can be optimised to offer a lower energy-demanding extrusion-based AM process. Alternatively, with respect to material options and availability for each extrusion-based AM method, material research and development remains key to improving materials into extrudable and printable resources. Importantly, as some materials may be more challenging to obtain, for example, by being costly with unsuitably long lead times, innovative material blends, alloys and composites appear to potentially offer viable solutions as these classes of material technologies advance; helping to bridge the gap of available materials. This is particularly relevant because of the geopolitical and supply chain uncertainties that have affected businesses in recent times and continues to be of concern for growing companies that look to take advantage of extrusion-based AM technologies in their offering of tailored and bespoke consumer products.

The environmental applicability of all extrusion-based AM process methods was good except for CODE, 3DCP and CFF. Importantly, as environmental applicability highlights the conditions for printability and operability, there needs be a balance of using the AM technology in an operable environment that supports printability. In the FDM or FFF method, printability can be more controlled due to the commonly used closed design 3DP architectures. However, for the open style 3DP architecture of FFF 3D printers, there is potentially more susceptibility to the conditions of the environment, which may support or hinder the suitability of using the AM process. 3DCP offers a typical challenging case where the process is mainly useful in large outdoor areas that are controlled by weather or climate conditions that need to be strongly considered prior to process design and process execution. In another instance, the CODE process uses a heat source, which, depending on the process design, may be unsuitable for use in a cooler environment, likely due to the possibility of higher operating costs. In this case a potential solution may involve enclosing the system, but this would consequently restrict potential scalability of the product size and hence the suitability, however depending on the intended part size. It seems to be an issue that requires a combined and robust machine-process-product-design and process planning regime that effectively considers the environment and intended scale of manufacturing. In terms of printability (and complexity), the extrusion-based AM process can be handier when the mechanism of this technology is hybridised, assuming optimal parameters have been defined for material processing. In this regard, multiheaded nozzle extruders can be employed in a multi-colour and multimaterial extrusion-based AM process to control complex filament flow conditions in conjunction with temperature and/or pressure controls. Employing a single nozzle extruder in the mechanism of this technology to print multicolour/material necessitates can amount to additional time for filament changing and nozzle cleaning in between multicolour or multi-type filament use. Therefore, the use of a multiheaded nozzle extruders can make the extrusion-based printing process less complicated and time-efficient; thereby increasing the suitability of this technology. Nonetheless, it was considered that using multi-headed extruder would increase the design complexity of the machine, which would lead to higher costs, etc. Perhaps the best approach in this case would involve creating optimized machine designs that strikes a good balance between the complexity of machine and DfM, as it suits business and project needs.

As the material and process developments improve for each extrusion-based AM process, their suitability and applicability also increase, and could lead to a future of highly strategic manufacturing systems that deliver unique value to customer and end-product users. With focus on the least suitable extrusion-based AM process, 3DCP, CFF, CODE and composite filament fabrication offer opportunities for improvements that could lead to greater adoption of their process systems. Considering the extrusion-based AM processes with low suitability, some adjustments can be made to improve the specific challenges restricting their suitability ratings. For instance, because 3DCP is limited to printing only a few materials, the mechanism of this process can be modified to be capable of printing various alternative AM materials by addition of some heating systems to melt the alternative or cement-based AM materials. Additionally, the robotic arms being used in this process can possibly be eliminated by using lightweight and foldable support mechanisms designed for print heads, to help overcome the issues associated with transporting big-scale printers to the construction sites. With regard to CFF, the high costs of CFF printers and carbon fibres, together with high operation costs, are some of the most impactful factors decreasing the suitability of this extrusion-based AM process. Nonetheless, there are some adjustments being made to make CFF widely used in industrial applications. An example includes the use of filaments modified by using more cost-effective filler materials (e.g. high-strength and high-performance plastics). As a result of such changes, the decrease in stiffness and strength of printed fibres can be minimised or neglected. Finally, the success in the CODE extrusion-based AM process is highly dependent on controlling the shrinkage of successively printed ceramics during the sintering stage of the fabrication process. Consequently, the sintering process can be taken into better consideration (by optimisation) to aid the fabrication of quality ceramic parts, which can lead to better densification of ceramic (green) parts with improved mechanical and functional properties.

6. Conclusions

The current paper has systematically reviewed the currently available and potential AM materials to be used in the extrusion-based AM by highlighting extrusion-based AM process characteristics linked with material options, and further considering their process- and material-centred suitability for eco-sustainable, efficient and effective extrusion-based AM process. The following conclusions can be deduced:

(1) The capabilities of extrusion-based AM process outperform compared to those of powder- and liquid-based AM processes, and conventional subtractive manufacturing process. In this regard, the favourableness of extrusion-based AM process, in comparison to the other manufacturing processes, is mainly because of the: (i) broad range of material option to use, (ii) low operating cost, (iii) high environmental applicability, and (iv) cost-effectiveness and basicness of this technology.

(2) The suitability rating of each individual type of extrusion-based AM process significantly varies based on the specific printing mechanisms and characteristic of each extrusion-based AM processes. Therefore, the suitability analysis for any extrusion-based AM process needs to be considered prior to any 3D printing application to meet the needs and demands of these applications.

(3) The melt extrusion and composite filament fabrication extrusion-based AM process offers the most promising opportunities for material developments that could help to create more

highly rated (cost-effective and simple) AM process systems that are capable of producing advanced or multifunctional parts or products.

(4) The suitability of FDM, FFF, DIW (robocasting), and bioprinting extrusion-based AM processes were considered as the most suitable extrusion-based AM processes for AM projects and production campaigns. On the other hand, CFF, CODE, and 3DCP were found to be relatively less suitable for AM projects; not because of their capability but mainly because of their safety, complexity, machine (operation) costs, and material- and process-restricted applicability.

(5) Improvements in the printability and complexity of each extrusion-based AM process to meet the increasing demand on customised AM products were found to be a factor increasing the respective machine (and operating) cost of extrusion-based AM processes. Although the increase in the total production cost, the capability of producing high-performance components were found beneficial for the suitability ratings of commercially available extrusion-based AM process.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Sadettin Cem Altıparmak: Conceptualisation, Methodology, Writing – Original draft & editing; Samuel I. Clinton Daminabo: Conceptualisation, Investigation, Writing – Original draft & editing.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Suitability analysis for extrusion-based additive manufacturing process

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