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Additive manufacturing (3D printing): A review of materials, methods, applications and challenges

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A B S T R A C T

Freedom of design, mass customisation, waste minimisation and the ability to manufacture complex structures, as well as fast prototyping, are the main benefits of additive manufacturing (AM) or 3D printing. A comprehensive review of the main 3D printing methods, materials and their development in trending applications was carried out. In particular, the revolutionary applications of AM in biomedical, aerospace, buildings and protective structures were discussed. The current state of materials development, including metal alloys, polymer composites, ceramics and concrete, was presented. In addition, this paper discussed the main processing challenges with void formation, anisotropic behaviour, the limitation of computer design and layer-by-layer appearance. Overall, this paper gives an overview of 3D printing, including a survey on its benefits and drawbacks as a benchmark for future research and development.

1. Introduction

3-D printing is an additive manufacturing (AM) technique for fabricating a wide range of structures and complex geometries from three-dimensional (3D) model data. The process consists of printing successive layers of materials that are formed on top of each other. This technology has been developed by Charles Hull in 1986 in a process known as stereolithography (SLA), which was followed by subsequent developments such as powder bed fusion, fused deposition modelling (FDM), inkjet printing and contour crafting (CC). 3D-printing, which involves various methods, materials and equipment, has evolved over the years and has the ability to transform manufacturing and logistics processes. Additive manufacturing has been widely applied in different industries, including construction, prototyping and biomechanical. The uptake of 3D printing in the construction industry, in particular, was very slow and limited despite the advantages e.g. less waste, freedom of design and automation.

New applications are emerging as novel materials and AM methods are continuously being developed. One of the main drivers for this technology to become more accessible is attributed to the expiry of earlier patents, which has given manufacturers the ability to develop new 3D printing devices. Recent developments have reduced the cost of 3D printers, thereby expanding its applications in schools, homes, libraries and laboratories. Initially, 3D printing has been extensively used by architects and designers to produce aesthetic and functional prototypes due to its rapid and cost-effective prototyping capability. The use of 3D printing has minimised the additional expenses that are incurred in the process of developing a product. However, it is only in the past few years that 3D printing has been fully utilised in various industries from prototypes to products. Product customisation has been a challenge for manufacturers due to the high costs of producing custom-tailored products for end-users. On the other hand, AM is able to 3D print small quantities of customised products with relatively low costs. This is specifically useful in the biomedical field, whereby unique patient-customised products are typically required. Customised functional products are currently becoming the trend in 3D printing as predicted by Wohlers Associates, who envisioned that about 50% of 3D printing will revolve around the manufacturing of commercial products in 2020 [1]. This technology has gained the attention of those in the medical field, due to its ability to produce a wide variety of medical implants from CT-imaged tissue replicas [2]. More recently, 3D printing is effectively being used in the construction industry. A group of relatively cheap houses in China ($4800 USD per unit) were successfully mass printed by WinSun in less than a day [3].

The growing consensus of adapting the 3D manufacturing system over traditional techniques is attributed to several advantages including

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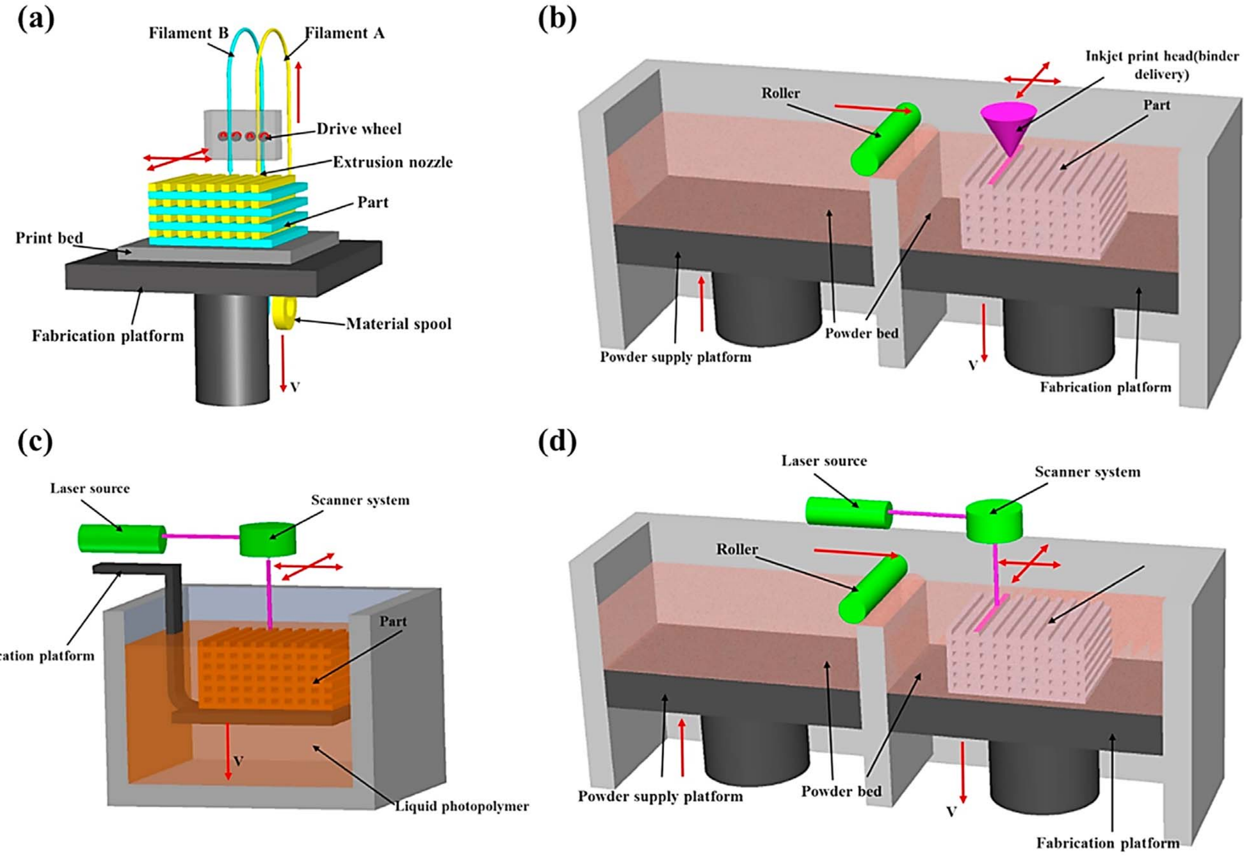

Fig. 1. Schematic diagrams of four main methods of additive manufacturing: (a) fused deposition modelling; (b) inkjet printing; (c) stereolithography; (d) powder bed fusion (courtesy of Wang et al. [13]).

fabrication of complex geometry with high precision, maximum material savings, flexibility in design, and personal customisation. A wide range of materials that are currently used in 3D printing include metals, polymers, ceramics and concrete. Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the main polymers used in the 3D printing of composites. Advanced metals and alloys are typically utilised in the aerospace sector because traditional processes are more time-consuming, difficult and costly. Ceramics are mainly used in 3D-printed scaffolds and concrete is the main material employed in the additive manufacturing of buildings. However, the inferior mechanical properties and anisotropic behaviour of 3D printed parts still limit the potential of large-scale printing. Therefore, an optimised pattern of 3D priming is important to control flaw sensitivity and anisotropic behaviour. Also, changes in the printing environment have an influence on the quality of finished products [4]. AM is capable of fabricating parts of various sizes from the micro-to macro-scale. However, the precision of the printed parts is dependent on the accuracy of the employed method and the scale of printing. For instance, micro-scale 3D printing poses challenges with the resolution, surface finish and layer bonding, which sometimes require post-processing techniques such as sintering [5]. On the other hand, the limited materials available for 3D printing pose challenges in utilising this technology in various industries. Hence, there is a need for developing suitable materials that can be used for 3D printing. Further developments are also needed to enhance the mechanical properties of 3D printed parts.

The advantages of 3D printing technology will continue to emerge through continuing research efforts, which must be undertaken to understand and eliminate constraints that inhibit the use of this technology. Design tools to assess life-cycle costs i.e., AM-oriented computer-aided design (CAD) systems with more user-friendly and advanced simulation capabilities are some of the key aspects that need to be realised. A distinguished advantage of 3D printing is mass customisation i.e., production of a series of personalised goods such that each product can be different while maintaining a low price due to mass production. 3D printing is devoid of the added cost due to mould making and tooling for a customised product. Therefore, mass production of a number of identical parts can be as cost-effective as the same number of different personalised goods. The change between different designs is straightforward with negligible added cost and no need for special preparation. AM also has the potential for mass production of complex geometries such as lattice structures, where the application of traditional methods of manufacturing such as casting is not straightforward and require further time-consuming tooling and post-processing. However, improvements in the fabrication speed and cost reduction must be resolved through the improvement of machine design. Also, the high costs and time-consumption of the AM process remain to be major hurdles that inhibit mass production.

This paper aims to provide a comprehensive review of 3D printing techniques in terms of the main methods employed, materials utilised, its current state and applications in various industries. The paper will also present research gaps and challenges encountered in adopting this technology.

2. Main methods

Methods of additive manufacturing (AM) have been developed to meet the demand of printing complex structures at fine resolutions. Rapid prototyping, the ability to print large structures, reducing printing defects and enhancing mechanical properties are some of the key factors that have driven the development of AM technologies. The most common method of 3D printing that mainly uses polymer filaments is known as fused deposition modelling (FDM). In addition, additive manufacturing of powders by selective laser sintering (SLS), selective laser melting (SLM) or liquid binding in three-dimensional printing (3DP), as well as inkjet printing, contour crafting, stereolithography, direct energy deposition (DED) and laminated object manufacturing (LOM) are the main methods of AM. These methods are briefly explained, their applications and suitable materials for each method are introduced, and their benefits and drawbacks are discussed. A comprehensive survey of these methods can be found in Bhushan and Caspers [6]. Novel emerging methods for specific applications such as: two-photon polymerization (TPP), projection micro stereolithography (PμSLA) and electrohydrodynamic printing (EHDP) were discussed by Mao et al. [7]; and non-contact micro and nano-printing methods were explained by Changhai et al. [8].

2.1. Fused deposition modelling (FDM)

In FDM method, a continuous filament of a thermoplastic polymer is used to 3D print layers of materials (Fig. 1a). The filament is heated at the nozzle to reach a semi-liquid state and then extruded on the platform or on top of previously printed layers. The thermoplasticity of the polymer filament is an essential property for this method, which allows the filaments to fuse together during printing and then to solidify at room temperature after printing. The layer thickness, width and orientation of filaments and air gap (in the same layer or between layers) are the main processing parameters that affect the mechanical properties of printed parts [9]. Inter-layer distortion was found to be the main cause of mechanical weakness [10]. Low cost, high speed and simplicity of the process are the main benefits of FDM. On the other hand, weak mechanical properties, layer-by-layer appearance, poor surface quality [11] and a limited number of thermoplastic materials are the main drawbacks of FDM [9]. The development of fibre-reinforced composites using FDM has strengthened the mechanical properties of 3D printed parts [12]. However, fibre orientation, bonding between the fibre and matrix and void formation are the main challenges that arise in 3D printed composite parts [12,13].

2.2. Powder bed fusion

Powder bed fusion processes consist of thin layers of very fine powders, which are spread and closely packed on a platform. The powders in each layer are fused together with a laser beam or a binder. Subsequent layers of powders are rolled on top of previous layers and fused together until the final 3D part is built (Fig. 1d). The excess powder is then removed by a vacuum and if necessary, further processing and detailing such as coating, sintering or infiltration are carried out. Powder size distribution and packing, which determine the density of the printed part, are the most crucial factors to the efficacy of this method [14]. The laser can only be used for powders with a low-melting/sintering temperature, whereas a liquid binder should otherwise be used. Selective laser sintering (SLS) can be used for a variety of polymers, metals and alloy powders while selective laser melting (SLM) can only be used for certain metals such as steel and aluminium. Laser scanning in SLS does not fully melt the powders and the elevated local temperature on the surface of the grains results in fusion of the powders at the molecular level. On the other hand, the powders are fully melted and fused together after laser scanning in SLM, which results in superior mechanical properties [15]. A detailed review of different materials and applications using SLM can be found in Ref. [16].

In the case of using a liquid binder, the method is referred to as three-dimensional printing or 3DP. The chemistry and rheology of the binder, size and shape of powder particles, deposition speed, the interaction between the powder and binder, and post-processing techniques play an important role in 3DP [13,14]. The porosity of parts printed by binder deposition is generally higher compared to laser sintering or melting, which can print dense parts [14]. Laser power and speed of scanning are the main parameters affecting the sintering process. Further details on different types of lasers and their effects on 3D printing can be found in Lee et al. [15]. Fine resolution and high quality of printing are the main advantages of powder bed fusion, which make it suitable for printing complex structures. This method is widely used in various industries for advanced applications such as scaffolds for tissue engineering, lattices, aerospace and electronics. The main advantage of this method is that the powder bed is used as the support, which overcomes difficulties in removing supporting material. However, the main drawbacks of powder bed fusion, which is a slow process, include high costs and high porosity when the powder is fused with a binder.

2.3. Inkjet printing and contour crafting

Inkjet printing is one of the main methods for the additive manufacturing of ceramics. It is used for printing complex and advanced ceramic structures for applications such as scaffolds for tissue engineering. In this method, a stable ceramic suspension e.g. zirconium oxide powder in water [17] is pumped and deposited in the form of droplets via the injection nozzle onto the substrate. The droplets then form a continuous pattern which solidifies to sufficient strength in order to hold subsequent layers of printed materials (Fig. 1b). This method is fast and efficient, which adds flexibility for designing and printing complex structures. Two main types of ceramic inks are wax-based inks and liquid suspensions. Wax-based inks are melted and deposited on a cold substrate in order to solidify. On the other hand, liquid suspensions are solidified by liquid evaporation. The particle size distribution of ceramics, viscosity of the ink and solid content, as well as the extrusion rate, nozzle size and speed of printing, are factors that determine the quality of inkjet-printed parts [18]. Maintaining workability, coarse resolution and lack of adhesion between layers are the main drawbacks of this method.

A similar technology to inkjet printing, called contour crafting, is the main method of additive manufacturing of large building structures. This method is capable of extruding concrete paste or soil by using larger nozzles and high pressure. Contour crafting has been prototyped to be used for construction on the moon [19].

2.4. Stereolithography (SLA)

SLA is one of the earliest methods of additive manufacturing, which was developed in 1986 [20]. It uses UV light (or electron beam) to initiate a chain reaction on a layer of resin or monomer solution. The monomers (mainly acrylic or epoxy-based) are UV-active and instantly convert to polymer chains after activation (radicalisation). After polymerization, a pattern inside the resin layer is solidified in order to hold the subsequent layers (Fig. 1c). The unreacted resin is removed after the completion of printing. A post-process treatment such as heating or photo-curing may be used for some printed parts in order to achieve the desired mechanical performance. A dispersion of ceramic particles in monomers can be used to print ceramic-polymer composites [18] or polymer-derived ceramifiable monomers e.g. silicon oxycarbide [21]. SLA prints high-quality parts at a fine resolution as low as 10 μm [13]. On the other hand, it is relatively slow, expensive and the range of materials for printing is very limited. Also, the kinetics of the reaction and the curing process are complex. The energy of the light source and exposure are the main factors controlling the thickness of each layer [20]. SLA can be effectively used for the additive manufacturing of complex nanocomposites [22].

2.5. Direct energy deposition

Direct energy deposition (DED) [23] has been used for manufacturing high-performance super-alloys. This method is also known as laser engineered net shaping (LENS™), laser solid forming (LSF), directed light fabrication (DLF), direct metal deposition (DMD), electron beam AM (EBAM) and wire + Arc AM (WAAM). DED uses a source of energy (laser or electron beam) which is directly focused on a small region of the substrate and is also used to melt a feedstock material (powder or wire) simultaneously. The melted material is then deposited and fused into the melted substrate and solidified after movement of the laser beam [23]. The difference between DED and SLM methods is that no powder bed is used in DED and the feedstock is melted before deposition in a layer-by-layer fashion similar to FDM but with an extremely higher amount of energy for melting metals. Therefore, it can be helpful for filling cracks and retrofitting manufactured parts for which the application of the powder-bed method is limited. This method allows for both multiple-axis deposition and multiple materials at the same time [24]. Moreover, DED can be combined easily with conventional subtractive processes to complete machining. This technique is commonly used with titanium, Inconel, stainless steel, aluminium and the related alloys for aerospace applications. In general, DED is characterised by high speeds (from 0.5 kg/h for LENS [25] to 10 kg/h for WAAM [26]) and very large work envelopes (up to 6 m × 1.4 m x 1.4 m for commercial printers) [27]. However, it has a lower accuracy (0.25 mm), lower surface quality and can manufacture less complex parts compared to SLS or SLM [23]. Therefore, DED is commonly used for large components with low complexity and also for repairing larger components. DED can reduce the manufacturing time and cost, and provides excellent mechanical properties, controlled microstructure and accurate composition control. This method can be used for repairing turbine engines and other niche applications in various industries such automotive and aerospace.

2.6. Laminated object manufacturing

Laminated object manufacturing (LOM) is one of the first commercially available additive manufacturing methods, which is based on layer-by-layer cutting and lamination of sheets or rolls of materials. Successive layers are cut precisely using a mechanical cutter or laser and are then bonded together (form-then-bond) or vice versa (bond-then-form). The form-then-bond method is particularly useful for thermal bonding of ceramics and metallic materials, which also facilitates the construction of internal features by removing excess materials before bonding. The excess materials after cutting are left for the support and after completion of the process, can be removed and recycled [28]. LOM can be used for a variety of materials such as polymer composites, ceramics, paper and metal-filled tapes. Post-processing such as high-temperature treatment may be required depending on the type of materials and desired properties. Ultrasonic additive manufacturing (UAM) is a new subclass of LOM which combines ultrasonic metal seam welding and CNC milling in the lamination process [29]. UAM is the only additive manufacturing method that is capable of construction of metal structures at low temperature [30,31]. LOM has been used in various industries such as paper manufacturing, foundry industries, electronics and smart structures. Smart structures are classified as structures (which can be multi-tasking) with a number of sensors and processors. Unlike conventional methods, UAM can specify cavities in the structure based on the integrated computer design for embedded electronic devices, sensors, pipes and other features. Electronic devices can be printed in the same lamination process of UAM using direct write technologies [28]. LOM can result in a reduction of tooling cost and manufacturing time, and is one of the best additive manufacturing methods for larger structures. However, LOM has inferior surface quality (without post-processing) and its dimensional accuracy is lower compared to the powder-bed methods. Also, removing the excess parts of laminates after formation of the object is time-consuming compared to the powder-bed methods. Therefore, it is not recommended for complex shapes.

Table 1 provides a summary of materials, applications, benefits, drawbacks and resolution range of the main methods of additive manufacturing.

3. Materials

3.1. Metals and alloys

Metal additive manufacturing is showing excellent perspectives of growth. The number of companies selling AM systems went from 49 in 2014 to 97 in 2016, amongst the 49% involved with metal AM [33]. This technology has been used predominantly for research, prototyping or advanced applications in the aerospace industry, e.g. manufacturing the F-15 Pylon Rib by Boeing [34]. It is also used in the biomedical, defence and automotive industries [33]. Metal AM provides great freedom for manufacturing complex geometries with special connections compared to conventional manufacturing methods. In particular, multi-functional components can be developed to provide solutions to structural, protective engineering and insulation problems at the same time.

Typically, the process of 3D printing metals consists of melting metallic feedstock (powder or wire) using an energy source such as a laser or an electron beam. The melted material is transformed layer by layer to form a solid part. The most commonly used techniques for printing metals are powder bed fusion (PBF) and direct energy deposition (DED) but there are other techniques that have been recently developed, such as binder jetting [35], cold spraying [36], friction stir welding [37], direct metal writing [38] and diode-based processes [39]. These processes can achieve higher accuracy or speed.

Many metallic materials such as stainless and tool steels, some aluminium alloys, titanium and its alloys, and nickel-based alloys can be manufactured using PBF-based AM processes [40]. PBF technologies can manufacture components with good mechanical properties and complex shapes with high accuracy (± 0.02 mm) [41]. However, these technologies are rather slow (up to 105 cm^3/h with four lasers) and are thereby mainly used for small parts. Studies are also being conducted on the use of different lasers, such as femtosecond lasers [42]. These ultrafast lasers allow for alloys and metals with high melt temperatures (> 3000 °C) and high thermal conductivity (> 100 W/mK), such as tungsten, rhenium and some ceramics.

Titanium and its alloys, steel alloys, a few aluminium alloys, nickel alloys, and some cobalt-based and magnesium alloys have been optimised for AM [40]. In particular, titanium and its alloys are high-performance materials commonly used in various industries [43,44]. They are characterised by high machining costs and a long lead-time based on conventional manufacturing methods. Thus, AM can offer significant economic advantages by producing very complex structures at lower costs with less waste. Ti [45] and Ti6Al4V [46] have been thoroughly studied and are currently being used for commercial applications in the aerospace and biomedical fields.

Steels such as austenitic stainless steels [47], maraging steels [48], precipitation hardenable stainless steels [49] and tool steels [50] are commonly used in AM. These alloys can be used for general applications but also for high strength and hardness conditions, such as for tools or moulding applications. Austenitic steels and precipitation hardenable stainless steels are particularly sensitive to AM parameters [49].

Only a few Al alloys are currently used in AM for several reasons. Compared with Ti alloys, they are easy to machine and their cost is low [51]. Therefore, there has been less commercial interest for their use in AM. Moreover, some high-performance Al alloys are hardly weldable (due to the high volatility of some of their elements, such as Zn) [52] and Al itself presents a high reflectivity for the laser wavelengths commonly used in AM [51]. Also, the low viscosity of the molten Al does not allow for a large melting pool and PBF is preferred over DED for its manufacturing. On a positive note, Al has a high thermal conductivity that reduces internal thermal stresses and allows for faster AM processes. At the moment, the most commonly used alloys are AlSi10 Mg [53] and AlSi12 [54].

Nickel-based superalloys (Inconel 625 [55] and 718 [56]) have been

Table 1
A summary of materials, application, benefits and drawbacks of the main methods of additive manufacturing.

Methods	Materials	Applications	Benefits	Drawbacks	Resolution range (μm)
Fused deposition modelling	Continues filaments of thermoplastic polymers Continuous fibre-reinforced polymers	Rapid prototyping Toys advanced composite parts	Low cost High speed Simplicity	Weak mechanical properties Limited materials (only thermoplastics) Layer-by-layer finish	50-200 μm [13]
Powder bed fusion (SLS, SLM, 3DP)	Compacted fine powders Metals, alloys and limited polymers (SLS or SLM) ceramic and polymers (3DP)	Biomedical Electronics Aerospace Lightweight structures (lattices) Heat exchangers	Fine resolution High quality	Slow printing Expensive High porosity in the binder method (3DP)	80-250 μm [13]
Inkjet printing and contour crafting	A concentrated dispersion of particles in a liquid (ink or paste) Ceramic, concrete and soil	Biomedical Large structures Buildings	Ability to print large structures Quick printing	Maintaining workability Coarse resolution Lack of adhesion between layers Layer-by-layer finish	Inkjet: 5–200 μm Contour crafting: 25–40 mm [32]
Stereolithography	A resin with photo-active monomers Hybrid polymer-ceramics	Biomedical Prototyping	Fine resolution High quality	Very limited materials Slow printing Expensive	10 μm [13]
Direct energy deposition	Metals and alloys in the form of powder or wire Ceramics and polymers	Aerospace Retrofitting Repair Cladding Biomedical	Reduced manufacturing time and cost Excellent mechanical properties Controlled microstructure Accurate composition control Excellent for repair and retrofitting	Low accuracy Low surface quality Need for a dense support structure Limitation in printing complex shapes with fine details	250 μm [23]
Laminated object manufacturing	Polymer composites Ceramics Paper Metal-filled tapes Metal rolls	Paper manufacturing Foundry industries Electronics Smart structures	Reduced tooling and manufacturing time A vast range of materials Low cost Excellent for manufacturing of larger structures	Inferior surface quality and dimensional accuracy Limitation in manufacturing of complex shapes	Depends on the thickness of the laminates

developed for high-temperature applications, while CoCr alloys [57] have been studied for biomedical and dental applications. Other materials such as Mg alloys [58] (for biomedical resorbable applications), Au [59] and Cu [60] have also been evaluated.

In general, dense metallic parts made with AM present comparable quality, if not better, to conventionally manufactured parts [40]. In order to accomplish this result, it is necessary to control porosity and microstructure. Porosity is the main defect resulting in crack propagation [61], which can be controlled by varying the applied volume energy [40] and the quality of the feedstock [62]. Low amounts of applied energy determine the formation of irregular-shaped voids in the material [63]. On the other hand, an excessive amount of energy generates spherical pores [61]. The quality of the feedstock can be improved with denser powder beds and by using smaller and regular spherical particles to improve flowability and homogeneity [62]. Also, the presence of contaminants and the quality of the alloy must be controlled.

In general, AM metal components present finer microstructures than conventional-manufactured parts and, consequently, increased yield and ultimate strengths [40]. However, their microstructure is anisotropic and determined by the building direction. Therefore, the anisotropy of the material properties with a higher tensile strength and strain in the direction of printing is common [56]. Surface roughness and material defects are also important for the fracture mechanical behaviour and fatigue strength of AM components. Increased surface roughness causes stress concentrations and earlier failure under fatigue loading [64]. Also, internal material defects and insufficient layer bonding decrease the fatigue resistance of AM parts.

The use of post-manufacturing treatments reduces residue porosity, transforms the microstructure and eliminates surface roughness. Hot isostatic pressing (HIP), which involves the application of an isostatic high pressure together with high temperatures on the component, and heat treatments, can eliminate residual porosities, increase ductility at the expense of strength and improve fatigue resistance [65,66]. Polishing or chemical etching of the surface can also improve the fatigue response of materials [64].

Research advancements in metallic materials and alloys for AM are increasing the range of usable materials. In particular, advanced studies are being conducted to implement high-entropy alloys, magnetic alloys, bulk metallic glasses (amorphous metals), high-strength alloys and functionally graded materials (FGM) [67,68] or metal composites. High-entropy alloys are composed of at least five principal metallic elements with an atomic percentage between 5% and 35% [69,70]. Consequently, many alloys with very different properties can be developed. These alloys can present higher strength-to-weight ratios, fracture resistance, tensile strength, corrosion and oxidation resistance than common alloys. CoCrCuFeNiAl [71], CoCrCuFeNiAlTi [72], AlCoCrFeNi [73], ZrTiVCrFeNi [74] and TiZrNbMoV [75] (the latter two for hydrogen storage purposes) were manufactured to exploit the high cooling rates that are typical in AM to obtain better microstructures [76].

Magnetic alloys can produce a constant magnetic field for a prolonged time. They are used in many fields, such as the aerospace, automotive, information technology and biomedical industries. Magnetic alloys that are currently being studied for AM applications include Ni-Fe-V, Ni-Fe-Mo [77], Fe-30%Ni [78] and Fe-Si-B-Cu-Nb [79]. Bulk metallic glasses (amorphous metals) are solid metallic materials with a disordered atomic-scale structure and an amorphous structure (random pattern in the atomic structure compared to the repeating pattern of conventional crystalline metals) [80]. These materials present superior tensile strength, high hardness, wear resistance, corrosion resistance and soft-magnetic properties compared to that of their crystalline counterparts. It is necessary to have a high cooling rate (~ 100 K/s) and at least one thin dimension for conventional methods for manufacturing of amorphous metals. Consequently, metallic glasses were manufactured only in rods or sheets. The use of AM allows for complex 3D structures, as shown in the work by Shen et al. [81].

A certain number of alloys are being used or studied for application or implementation in AM. However, the vast majority of the metal alloys used today (more than 5500) cannot tolerate AM processes because the melting and solidification dynamics would create inadequate microstructures, such as columnar grains and periodic cracks [82]. A new study from Martin et al. [83] demonstrates that it is possible to resolve these issues by using nanoparticles, which nucleates during AM to control the solidification of the alloys. They applied their methodology in order to make strong Al alloys (Al 7075 and 6061) that previously could not be manufactured properly with AM. The nucleants were selected using the crystallographic information. The manufactured Al alloys presented crack-free, equiaxed and fine-grained microstructures with similar mechanical properties to the wrought materials. The methodology was applied to SLM but is also applicable to EBM and DED processes or conventional manufacturing methods. Moreover, it will allow for AM with non-weldable nickel superalloys and other alloys.

The development of FGM is another critical area of study that takes advantage of AM processing efficiency. Developing methodologies for manufacturing materials with site-specific properties is fundamental to increasing the efficiency of components. Smooth transitions between alloys have been obtained using LENS [84] or friction stir AM [37]. In order to properly design these gradients, it is necessary to use multi-component phase diagrams to evaluate which phases will appear at the interface between the two alloys and assess the possibility of the formation of undesired phases [84]. Moreover, a multi-component phase diagram with three materials (or more) can be developed for designing a path using the third alloy as an intermediate passage [85]. Another method that can alter material properties without changing the type of alloys is to change the process parameters, such as the energy power [86].

An additively manufactured 316L lattice has been infiltrated by molten A356 (with a significantly lower melting temperature). The stress-strain response and the thermal conductivity of the lattice structure were optimised by varying the geometry and density. At the same time, tensile elongation increased by one order of magnitude when compared with the original A356. These results were obtained because the adopted infiltration processing method avoided intermetallic formation, cracking and poor resolution, thereby solving common problems that are encountered in traditional AM techniques for printing metallic composites.

Additive manufacturing of metals facilitates the fabrication of complex components made with expensive materials, such as titanium and its alloys, which are important for the aerospace and biomedical industries. AM of metals is a rapidly evolving; where new methods, alloys and applications are announced more frequently with significant quality improvements and reduced manufacturing times. In particular, research and investments from governments, universities and private companies aim to increase the speed and accuracy of AM, as well as expand the number of available alloys while keeping an eye on price reduction. AM has the potential for the mass production of high-quality products if combined with conventional manufacturing processes. The benefits of metal additive manufacturing are reduced tooling costs, freedom of design and manufacturing of complex and lightweight structures, and multiple part consolidation, which can eliminate part assemblies.

3.2. Polymers and composites

Polymers are considered as the most common materials in the 3D printing industry due to their diversity and ease of adoption to different 3D printing processes. Polymers for additive manufacturing are found in the form of thermoplastic filaments, reactive monomers, resin or powder. The capability of employing 3D printing of polymers and composites has been explored for several years in many industrial applications, such as the aerospace, architectural, toy fabrication and medical fields. Some of the benefits of fabricating composites using 3D printing include the ability to customise geometry with high accuracy. Also, this process can be more cost-effective than other traditional formative methods, such as moulding and extrusion for customised products. On the other hand, pure polymer products built by 3D printers are only often used for conceptual prototypes due to the inherent lack of strength and functionality. Ongoing research aimed at resolving the inferior mechanical properties of 3D printed polymers has been conducted, which led to the development of various methods and materials for manufacturing advanced polymer composites with better performance [13,87].

Photopolymer resins can polymerise when activated by UV light in stereolithography 3D printing. According to the annual industry survey conducted by Wohlers Associates, nearly 50% of the 3D printing market in the industrial sectors is attributed to generated prototypes using photopolymers [88]. However, the thermomechanical properties of photopolymers should still be improved. For instance, molecular structure and alignment of 3D printed polymers depend on the thickness of the layers because of the gradient in UV exposure and intensity [89,90]. On the other hand, plastic for selective laser sintering (SLS) is reported to be the second most important class for 3D printing. Among SLS polymers are polystyrene, polyamides and thermoplastic elastomers [88].

Accuracy, thin layers and fine precision are offered by photopolymer-based systems. Further developments using new resins have improved strength and temperature resistance. Thermoplastic polymers (e.g. acrylonitrile-butadiene-styrene copolymers (ABS) [91], polycarbonate (PC) [92] and polylactic acid (PLA) [93]) could be processed by various 3D printing methods. Although maintaining an optimum resin viscosity at low temperature is a key challenge to utilising PLA, two solutions can resolve this problem: 1. increasing the temperature during processing and 2. using an appropriate plasticizer. The latter solution is more advantageous as it prevents thermal degradation.

PLA-based composite blends are currently being used for the fabrication of 3D-printed scaffolds for tissue engineering. Senatov et al. [94] confirmed the presence of interconnected pores within the structure of PLA-based scaffolds by SEM imaging as presented in Fig. 2. A combination of PLA and a bioactive CaP glass was 3D printed to develop 3D porous bio-compatible scaffolds for various tissue engineering applications [95]. Additionally, polymeric cellular materials are fabricated through processes which involve the use of chemical or physical blowing agents. Another technique for fabricating these cellular materials is 3D printing, where Abueidda et al. [96] investigated the mechanical properties of three triply periodic minimal surfaces (TPMS) to create new polymeric cellular materials.

Various 3D printing techniques are available for fabricating polymers and composites namely; stereolithography, SLS, FDM, 3D bioprinting and inkjet printing. FDM is most commonly used for the fabrication of polymer composites and thermoplastics with low melting points [13]. However, eco-friendly polymeric materials with good

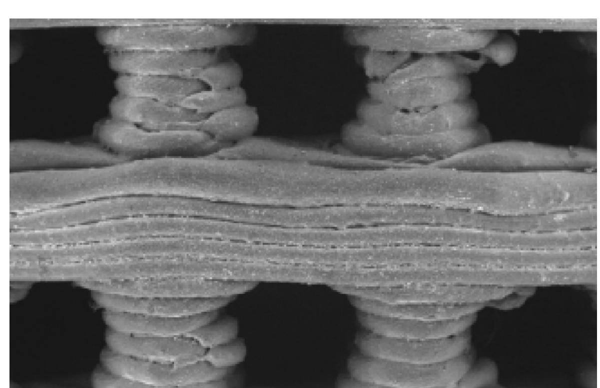

Fig. 2. 3D printed PLA-based porous scaffold (courtesy of Senatov et al. [94]).

physical properties are of major concern for FDM because common commercial polymers for 3D printing, such as ABS and PLA, do not meet the required outputs. ABS has good mechanical properties but emits unpleasant odour during processing whereas PLA is environmentally friendly but has poor mechanical properties [97]. Research by Song et al. [98] demonstrated that 3D-printed PLA showed enhanced mechanical properties compared with injection-moulded PLA i.e., elasto-plastic, orthotropic behaviour with a robust asymmetry in both compression and tension. Post-tensioning of natural-fibre reinforcement embedded in the PLA matrix also improved mechanical properties [99].

The addition of fibre reinforcement can enhance the mechanical properties of polymers and is a promising advancement in 3D printing [100–102]. Recently, researchers have found it challenging to develop continuous fibre reinforcement for improving the mechanical properties of 3D-printed polymer composites [12]. A study by Tekinalp et al. [103] highlighted the challenges associated with 3D printing fibre reinforced composites and evaluated the load bearing potential of composite parts made from carbon fibre and ABS resin feedstock. The samples fabricated through FDM and compression-moulding (CM) resulted in a significant increase in strength and stiffness. Moreover, the higher strength of the CM samples showed that fibre orientation has a lesser effect than porosity on the tensile properties. Furthermore, the mixture of CF with polymer feedstock will result in increased strength and stiffness, and reduced distortion of the final 3D printed parts [104].

Bakarich et al. [105] demonstrated the use of 3D printing in preparing fibre reinforced hydrogel composites in a single step process using alginate/acrylamide gel as a precursor and a UV-curable adhesive. Improvements towards using appropriate ink resolutions will result in creating complex composites that are based on hydrogel materials. AM technology was utilised to design and fabricate reinforcing elements of cement mortar based on 3D printed fibres made of photopolymers and titanium alloy. The utilisation of this technology-enhanced matrix toughness and exhibited a different surface morphology. This research highlighted the dependency of shear capacity, flexural strength and fracture toughness of the reinforcing fibres. It was also observed that when fibre surface design is optimised, the energy absorption capacity of fibre-reinforced mortars may significantly increase [106]. Alumina powders were used to reinforce polymer matrix for manufacturing of a wear-resistant material to be used as a filament in FDM [107,108] or as nanofillers in SLM methods [109].

Other emerging materials for 3D printing are nanomaterials, which are capable of lowering sintering temperatures and improving mechanical and electrical properties [110–114]. Nanomaterials can be introduced in a 3D printed part either manually or automatically with intermittent stoppages or through pre-mixing into the host matrix. Although utilising nanomaterials and AM pose numerous advantages, homogeneity of the products can be improved. Nanocomposites have attracted the attention of various industries due to several attractive properties, such as good thermal conductivity, enhanced fire performance, excellent strength and lightweight [115,116]. There is significant potential for nanocomposite production when nanomaterials are integrated and blended into host matrices through 3D printing. Hence, developing the production of nanocomposites in terms of consistency and reliability, cost, and thermal instability could offer advantages and new opportunities. Postiglione et al. [91] developed a low-cost liquid deposition modelling (LDM) 3D printing technique for fabricating conductive 3D microstructures with arbitrary shapes from polymer nanocomposite materials based on PLA and multi-walled carbon nanotubes. As presented in Fig. 3, a woven structure was fabricated for a simple electrical circuit using this technique. Weng et al. [117] investigated the application of three different nanoparticles, namely nano SiO_2, montmorillonite and attapulgite, into the stereolithographic resin to form nanocomposites. They concluded that nano SiO_2 exhibited the best reinforcement effect. The research also paved the way for nanocomposites to be applied in desktop level SLA 3D printing. A Nylon 6 based nanocomposite material was studied for its potential as an FDM filament material. Through SEM, it was observed that the nanoparticles are uniformly dispersed. Therefore, Nylon 6 can be used as an alternative to ABS, and consequently, can be widely used in 3D printing [118]. Although there has been significant work on designing nano-fillers for 3D printing composites, the aggregation of nanoparticles and severe light scattering owing to its high nano-filler content is still the main challenge for the development of this novel material [113]. Although there has been significant work on designing nano-fillers for 3D printing composites, the aggregation of nanoparticles and severe light scattering owing to its high nano-filler content is still the main challenge for the development of this novel material [113].

Fig. 3. 3D printed multi-walled carbon nanotube-based nanocomposite (courtesy of Postiglione et al. [91]).

In other research by Shofner et al. [119], vapour-grown carbon fibre (VGCF), which is a practical type of single-walled carbon nanotube, was used as a nanofiller to strengthen ABS. VCGFs have gained a lot of attention due to their superior thermal and electrical properties in a polypropylene matrix. The research showed how the processes of extrusion, FDM and Banbury mixing (used for mixing polymers and compounding plastics) generated a good quality composite material with a uniform distribution of fibres and minimal porosity. It was also suggested that extrusion or shear processing is effective in aligning nanofibers. VCGF-filled ABS resulted in increased tensile strength and stiffness. However, a brittle fracture mode was observed and further fibre treatment was suggested to increase adhesion. Carbon nanotube reinforced ABS (CNTABS) and short carbon fibre reinforced ABS (CFABS) also showed improved mechanical properties [120–122]. Utilising the inkjet printing technique with silver (Ag) nanoparticle as ink, Krivec et al. [123] introduced a rapid packaging technique for the construction of a simple radio frequency identification package, which proved to be suitable for advanced package prototyping. Elliott et al. [124] investigated the effect of incorporating nanoparticles called Quantum Dot (QD) onto photopolymer resin in which Polyjet direct 3D printing was utilised. QD is a type of nanoparticle which is 2–20 nm in diameter and is capable of absorbing ultraviolet (UV) light. It was observed that by adding nanoparticles, the rheology of the material is altered. The integration of this material with 3D printing technology gives an end product that has unique optical properties.

3D printing of polymer composites has been developed over the years, whereby new materials are being investigated and explored. The integration of 3D printing and a polymer matrix composite offers significant potential for industrial manufacturing with exceptional functionality and mechanical performance [125]. However, the limitation of printable materials, which can adapt the method of 3D printing for broader industrial applications of high-performance composites, still remains a key challenge. The speed of AM of composites and repeatability are inferior to traditional methods. However, interest in moving from rapid prototyping to mass customisation of working parts has been growing steadily. With this transition, new materials could also be developed by synthesising other matrix materials, which can lead to excellent mechanical properties. Hence, there is a need for further research to explore more suitable materials and applications for 3D printing polymer composites.

3.3. Ceramics

AM has become an essential method for manufacturing of advanced ceramics for biomaterials and tissue engineering e.g. scaffolds for bones and teeth [126]. Despite the accuracy of printing, layer-by-layer appearance and a limited selection of materials are the main challenges for 3D printing of ceramics [18]. Post-processing of sintered ceramic parts for forming the desired shape is a time-consuming and costly process. Therefore, 3D printing of complex shapes followed by sintering to produce ceramics with complex shapes has become very attractive. Moreover, 3D printing of porous ceramics or lattices introduced numerous benefits by developing advanced lightweight materials that are tailored for different applications. Ceramic scaffolds used in tissue engineering have become more convenient and faster compared to traditional methods of casting and sintering [126].

In addition, 3D printing has the advantage of controlling the porosity of lattices [127]. Different methods and materials have been investigated, which are aimed at improving the mechanical properties of 3D printed ceramic lattices compared to traditional methods. Li et al. [128] developed a porous alumina ceramic with the addition of $CaSO_4$ and dextrin, which showed a very high flexural strength. On the other hand, Maurath and Willenbacher [129] showed that by improving the process of ink-printing in terms of rheology and homogeneity of the ceramic suspension, as well as optimised sintering, a honeycomb structure with a high specific strength can be made with no cracking and better dimensional stability. Minas et al. [130] investigated the mixture of 3D printed ceramic foam ink into a hierarchal porous ceramic with a high strength to weight ratio. In this method, larger pores were achieved by 3D printing the lattice structure (i.e., the space between filaments during printing) and micro-pores were created by the air bubbles within the foam itself.

The main methods of 3D printing ceramics are inkjet (suspension), powder bed fusion, paste extrusion and stereolithography. Inkjet is deemed to be the main method of making dense ceramic samples that may not need post-treatment [18]. A stable suspension with controlled rheology that easily flows, does not clog at the nozzle and has an effective drying process is required for 3D inkjet printing [131]. Breaking and thinning of the printed filament is also deemed to be an important aspect of inkjet printing of ceramic suspensions and the viscoelastic behaviour of inks is the controlling factor [132].

Selective laser sintering (SLS) of powder is also a common method for 3D printing ceramic powders. However, thermal shock of fusion heating and cooling down to room temperate can lead to crack formation in ceramic parts [18]. Selective laser gelation (SLG) which combines SLS and sol-gel technique has been also introduced for ceramic-matrix composites [133]. For ceramic powders that do not easily fuse or melt at a lower temperature of laser heating, a binder with a lower melting temperature is used. The laser-activated binder temporarily holds the ceramic powder in the desired shape, and the green body, after removing the excess powder, is then sintered at a higher temperature for solidifying the ceramic powder. The auxiliary binder may be removed after sintering. This method is known as indirect SLS and is generally used for ceramic-glass and ceramic-polymer composites. However, Vorndran et al. [134] used phosphoric acid as the binder for making β–tricalcium phosphate ceramics, which resulted in a higher printing resolution, higher mechanical performance and faster settings, thereby simplifying the process of removing the binder from the powder bed after printing. Ceramics made by the SLS method typically have a lower density and higher porosity compared to the cast ceramics unless they are post-treated by sintering [18]. The particle size distribution of ceramics also affects the flowability, density and shrinkage of the printed sample. In a glass-ceramic system, it is shown that a higher portion of finer particles decreased the flowability, which resulted in a lower printing resolution and higher shrinkage. Also, the lower bulk density of glass-ceramic powder (inferior packing) results in higher shrinkage during sintering [135].

Extrusion of ceramic paste or filament is also known as extrusion free-forming of ceramics (EFF), fused deposition modelling of ceramics (FDC) or rapid prototyping (RP). The main methods of post-curing for extruded ceramics are phase changing (i.e., crystallisation of liquid phase by freezing or freeze-drying), evaporation of water or solvent and UV or heat curing. Rheology is one of the main controlling properties for ceramic paste extrusion and high viscosity slurries are not suitable for 3D printing of ceramics [136]. Besides the particle size distribution and packing of particles in the paste, the liquid to solid ratio, air-entrapment, temperature, drying and de-binding procedure, solidification kinetics and inter-layer adhesion can affect the properties of 3D printed ceramics [18]. Stereolithography, in spite of being developed for 3D photopolymerization (UV, laser or LEDs can also be used) of monomer into polymers, has been extended to ceramic materials.

Direct ceramic stereolithography (CSL) uses a photocuring binder with a high amount of ceramic fillers, which is then heat-cured to achieve the green body of the ceramic. In order to have better light curing of the binder, smaller ceramic particles with better light scattering properties are preferred in this method [18]. Laser printing of a nano-ceramic resin has been also developed [137]. On the other hand, polymer-derived ceramifiable monomers e.g. silicon oxycarbide can be 3D printed, polymerised by UV and then sintered at a higher temperature to form high-quality complex ceramic lattices [21]. The process of 3D printing polymer-derived ceramics is shown in Fig. 4. Polymer-derived ceramics have the advantage of not requiring post-processing to remove the organic binder compared to the method of using ceramic fillers, which thereby shortens, the manufacturing time. CSL can produce a very smooth surface finish. However, it is an expensive process and a limited number of materials available for this technique are considered to be the main drawbacks [18]. Stereolithography of alumina ceramics with additional liquid infiltration of samples in zirconium or magnesium solutions followed by in-situ precipitation has been studied by Liu et al. [138]. The results showed remarkable improvements in strength compared to that without

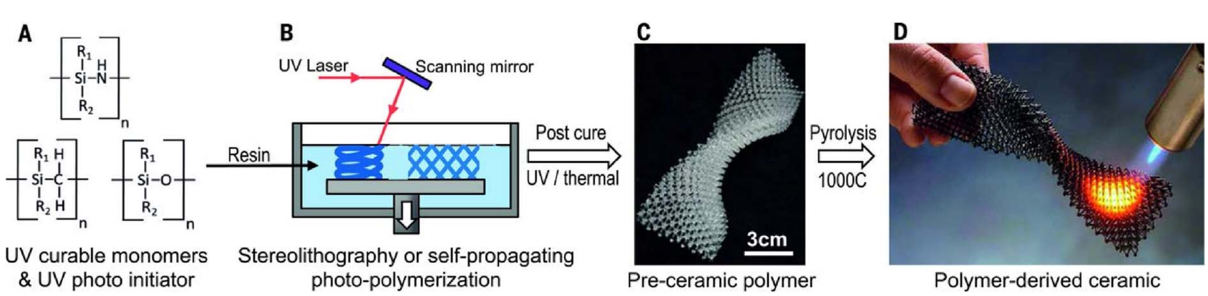

Fig. 4. The process of 3D printed polymer-derived ceramics (courtesy of Eckel et al. [21]).

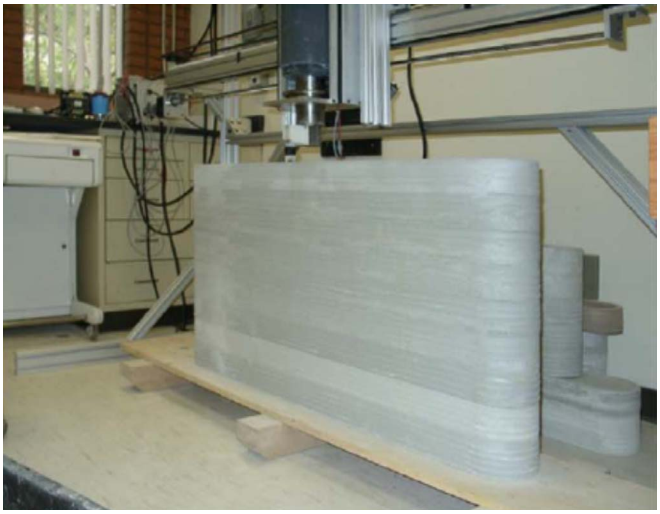

Fig. 5. 3D printed concrete structure (courtesy of Zareiyan and Khoshnevis [148]).

infiltration but lower fracture toughness. Although the particle size distribution of ceramic powder in the paste is not a dominant factor compared to the powder printing by SLS technique, it can affect the properties of a 3D printed part by stereolithography. Dehurtevent et al. [136] showed that particle size has no impact on the flexural strength or shrinkage of printed samples of alumina for a dental crown. On the other hand, Wu et al. [139] showed that using a bimodal distribution of particles i.e., a combination of micro-sized and nano-sized alumina particles contributed to higher density compared to the mono-sized distribution of alumina particles.

3.4. Concrete

Additive manufacturing technology has been expanded to the construction industry. A similar technology to inkjet printing, called contour crafting, as the main method for the additive manufacturing of building structures, has been developed [19]. This method uses larger nozzles and high pressure to extrude the concrete paste. In order to have a smooth finish instead of a layer-by-layer appearance, a trowel-like apparatus has been designed that is attached to the printhead [19]. Currently, 3D printing technology for the construction industry is in its infancy. Therefore, the life-cycle performance of the technology is yet to be determined. A limited number of recent academic studies on 3D printing concrete structures have developed different methods and materials, which are briefly discussed hereafter.

The fresh properties of concrete are the most important aspects of successful contour crafting. The 3D printing of complex shapes requires high workability for extrusion i.e., extrude-ability or open time, and high early strength of concrete to support subsequent layers i.e., build-ability [140]. A mix design that can satisfy the requirement of prolonged workability before setting for extrusion but at the same time have high early-strength to support subsequent layers without collapsing requires a well-designed material and equipment. Gosselin et al. [141] developed a printing process that pumps the accelerator and the premix mortar in separate tubes and then combines it at the printhead before extrusion. In this method, the rheology of the premix mortar can be controlled for a longer period without sacrificing the early strength of the printed layers in order to successfully build up the subsequent layers. This method would be able to build larger structures with complex geometries and without temporary supports by using a six-axis robotic arm and controlling the material behaviour during and after the extrusion process. Paul et al. [142] investigated different concrete mixtures and found that the rheological properties of the concrete mixture, especially thixotropic behaviour, is an influencing factor for pumping and printing these mixtures. Perrot et al. [143] established a theoretical framework based on the rheological behaviour of a cement mixture in order to optimise the building rate without fracturing and deforming of the bottom layers. Le et al. [140] developed a high-performance 3D printed polypropylene fibre-reinforced mortar compromising of Portland cement, fly ash, silica fume and sand (maximum aggregate size of 2 mm). The addition of superplasticizers and retarder showed adequate workability for extrusion through a 9 mm diameter nozzle with an open time of 100 min. The developed mixture has a build-ability of up to 61 layers (about 400 mm).

3D printed fibre-reinforced concrete composites bring the benefit of controlling fibre orientation in a printed structure compared to traditional fibre-reinforced concrete. Freedom of the orientation of carbon fibres along different printing paths significantly increased flexural strength by up to 30 MPa in the case of printing parallel lines in the x-y plane [144]. Zhong et al. [145] investigated a 3D printed nanocomposite geopolymer i.e., an alkali-activated, Portland cement-free concrete. The nano-graphene oxide in the geopolymer system resulted in proper rheological properties for extrusion, the higher compressive strength of about 30 MPa and increased electrical conductivity. A mix of rapid hardening cement and polyvinyl alcohol (PVA) composite was used in order to print with a finer resolution. However, layer delamination and void formation between the layers were observed, which became less distinct after post-curing of the samples in water [146]. Zhu et al. [147] investigated a mix design of a cementitious mortar, using OPC and sulphoaluminate cement (SAC) as raw materials. The primary difference between these two materials is the setting time; SAC is characterised by its short setting time and high early strength whereas OPC has slow hydration and a longer setting time. After examining these two materials, SAC was proposed to be a more appropriate material for 3D printing mortar due to its properties. The early setting time is deemed to be essential in 3D printing because of its process of printing by layers, which allows bottom layers to gain adequate strength to support the top layers. Paul et al. [142] concluded that the printing parameters, such as the shape of the nozzle, controls the mechanical properties of the specimens, which are governed by the printing directions.

Interlayer adhesion is one the main challenges of 3D printed concrete structures. Zareiyan and Khoshnevis [148] investigated the effects of aggregate size, extrusion and layer thickness on the bond strength between layers. Their 3D printed concrete structure is shown in Fig. 5. They found that the smaller maximum aggregate size and higher cement to aggregate content resulted in higher strength because of the better interlayer bonding. The increased thickness of the layers with more time lapse between subsequent layers, despite better interlayer bonding, reduced the compressive strength of the printed structure. Also, a shorter setting time may increase the possibility of cold joints between layers [148]. Shape-stability of the printed part is defined as the stability of the printed layers against settlement and deformation caused by printing of the subsequent layers. Kazemian et al. [32] showed that the addition of silica fume and nano-clay can remarkably increase the shape-stability of 3D printed cement paste. The other main challenge of building 3D printed complex and tall structures is the lack of appropriate external support and its removal after the construction [149].

Despite the main focus of 3D printing on cement and concrete paste, the powder bed fusion method has been also investigated. Shakor et al. [150] used a mix of ordinary Portland cement and calcium aluminate cement as the powder bed with an aqueous solution of lithium carbonate as the binder. A compressive strength of about 8 MPa, considerably high porosity of about 50% and limited hydration due to limited powder-water contact were observed. Xia and Sanjayan [151] investigated a 3D printed powder structure in a geopolymer system. The powder bed consists of ground blast furnace slag, sand and ground anhydrous sodium silicate i.e., alkali activator. The liquid binder consists of water with a small amount of 2-Pyrrolidone. The printed cubes have a very low strength of 0.9 MPa with the dimensional expansion of less than 4%. Post-treatment of the samples in an alkali solution at 60 °C increased the strength up to 16.5 MPa. However, treatment of the alkali solution and high temperature are deemed to be implausible in full-scale 3D printed structures.

Challenges in the 3D printing of wet concrete are not only attributed to controlling fresh properties of concrete in order to have sufficient workability and open time for extrusion but also the structural properties e.g. strength, inter-layer adhesion, deformation and build-ability. The durability of 3D printed structures should also be investigated. For instance, a 3D printed structure can have accelerated evaporation of water because of the lack of formwork to protect against air exposure compared to conventional concrete. This can consequently increase the shrinkage and the risk of cracking. Powder-bed AM needs to be further developed in order to create high-strength structures. Despite current challenges, freedom of design and building complex structures with cheaper materials such as concrete have been the main initiatives of researchers that are developing 3D printed concrete. The development of different concrete mixtures for 3D printing resulted in the manufacturing of 3D printed structures and houses around the world, which will be discussed in Section 4.3. The next generation of 3D printed structures has the opportunity to be exploited for construction on the moon [19,152].

3.5. Comparison of different materials for 3D printing

A diverse range of materials from chocolate to advanced multi-functional materials can be 3D printed as a result of fast development in additive manufacturing technologies. Materials in the forms of filaments, wire, powder, paste, sheets and inks can be used for 3D printing. Polymers are considered as the most common materials that have been developed for aerospace, automotive, sports, medical, architectural and toy industries. Polymers used in 3D printing are mainly in the form of filaments in FDM (the most common method), powders or auxiliary binder in the powder-bed method or resins in stereolithography. Thermoplastic polymers such as acrylonitrile-butadiene-styrene copolymers (ABS), polyamide (PA), polycarbonate (PC) and polylactic acid (PLA), and thermosetting powders such as polystyrene, polyamides and photopolymer resins, are the most common types of polymers for 3D printing. Due to lack of mechanical properties, 3D printed polymers are mainly used for fast prototyping. However, the reinforcement of polymers with fibres and nano-materials has been introduced in recent years with the aim of enhancing the mechanical properties of the printed products to be used as load-bearing or functional components.

Additive manufacturing results in the waste reduction of expensive metals such as titanium compared to traditional methods. It also eliminates the assembly phase, reduces the risks of localised stresses in the assembly process and substantially increases the freedom of design. The aerospace, defence and automotive industries are taking advantage of 3D printing of metals and alloys in the manufacturing of complicated parts of various sizes. Metals are mainly in the form of powders (or wires). SLS, SLM and DED are the main methods of 3D printing which are all based on the fusion of powders by melting or sintering using a laser or electron beam. A limited selection of metal and alloys suitable for 3D printing resulted in continuous research and development to increase the number of available alloys and polymer-metal composites [153], adoption of current techniques to a broader range of materials and also to develop composite structures. Defects such as porosity, accumulations of beads, and the variability of material properties and shapes, which depend on the orientation of the parts, still limit the possibilities of metal 3D printing. However, studies on the enhancement of processing parameters and post-processing treatments are ongoing.

3D printed ceramics have created a trend to tailor-design materials with a high strength to weight ratio and facilitated the creation of complex ceramic lattices for many applications. In particular, strong and versatile ceramic scaffolds with complex shapes for tissue engineering is one of the main applications. Ceramics are mainly 3D printed in the form of powders or ink. Powders are sintered using laser or bond together via an auxiliary adhesive. On the other hand, ink-jet printing is used to print a suspension of ceramic particles followed by post-treatment e.g. high-temperature sintering. The main challenge is the limited number of materials for 3D printing ceramics by current methods, as well as dimensional accuracy and quality. On the other hand, 3D printing of ceramics provides better control over the microstructure and composition of the part. Therefore, research and development in the optimisation of AM technologies, as well as the expansion of materials selection for 3D printing of ceramics, are opportunities that are yet to be exploited.

Concrete is the most used man-made material, which is consumed in construction and infrastructure projects around the world. The intake of 3D printing by the construction industry has been slow but the advantages such as mass-customisation, no required formwork and automation promise a bright future in this area. Extrusion is the main method used for the additive manufacturing of concrete, although the powder-bed method has been also explored. The type of concrete suitable for 3D printing can be very different. As an example, pumpable concrete may not have enough shape-stability and dimensional accuracy after printing, even though it is good for the extrusion process of 3D printing. Self-compacting concrete may not be suitable for 3D printing as it may not hold its shape in the formwork-free method of 3D printing. Also, layer-by-layer appearance, anisotropic mechanical properties and poor inter-layer adhesion are the main challenges that need to be addressed. Despite these challenges, freedom of design and opportunity to build complex and lightweight structures are promising. Table 2 provides a summary of the main applications, benefits and challenges of the main materials for additive manufacturing.

Current 3D printing technologies can tailor the multifunctional properties of the manufactured parts by combining different materials and controlling their position precisely [154]. Some of them are able to vary materials between layers, while others can change the materials also within a layer. However, there exist some limitations. For instance, high-pressure jetting systems can combine only polymers with good flowability and similar curing temperatures and extrusion-based methods, such as FDM, can couple only materials with similar melting temperatures [154]. Multi-jet FDM methods are gaining more attention in bioprinting applications and particularly in the manufacturing of complex hydrogel scaffolds combined with cells to mimic the tissue matrix [155]. Other 3D printing technologies, such as DED, allow for the combination of metal alloys or ceramics, and as a result, more materials can be extruded at the same time. However, additional care must be taken to avoid the formation of unwanted phases between two materials in contact [85]. Some success in using powders with different melting temperature in powder-based technologies has been attained [154,156]. However, issues can be encountered due to remelting or degradation of materials with lower melting points adjacent to the powders with higher melting points. Also, the development of numerical modelling and optimisation techniques of material processing can help with the multi-material manufacturing processes and their multi-functional responses [157].

4. Trending applications

4.1. Biomaterials

A recent Wohlers' report [33] forecasts that the additive manufacturing industry will grow from $6.1 billion in 2016 to $21 billion by the year 2020. The biomedical market represents 11% of the total AM market share today and is going to be one of the drivers for AM evolution and growth.

Biomedical applications have unique necessities:

- *High complexity.* Biomedical research is challenged by the complexity and innovative approaches. AM will allow the development

Table 2
A summary of main applications, benefits and challenges of the main materials for additive manufacturing.

Materials	Main applications	Benefits	Challenges
Metals and alloys	Aerospace and Automotive Military Biomedical	Multifunctional optimisation Mass-customisation Reduced material waste Fewer assembly components Possibility to repair damaged or worn metal parts	Limited selection of alloys Dimensional inaccuracy and poor surface finish Post-processing may be required (machining, heat treatment or chemical etching)
Polymers and composites	Aerospace and Automotive Sports Medical Architecture Toys Biomedical	Fast prototyping Cost-effective Complex structures Mass-customisation	Weak mechanical properties Limited selection of polymers and reinforcements Anisotropic mechanical properties (especially in fibre-reinforced composites)
Ceramics	Biomedical Aerospace and Automotive Chemical industries	Controlling porosity of lattices Printing complex structures and scaffolds for human body organs Reduced fabrication time A better control on composition and microstructure	Limited selection of 3D-printable ceramics Dimensional inaccuracy and poor surface finish Post-processing (e.g. sintering) may be required
Concrete	Infrastructure and construction	Mass-customisation No need for formwork Less labour required especially useful in harsh environment and for space construction	Layer-by-layer appearance Anisotropic mechanical properties Poor inter-layer adhesion Difficulties in upscaling to larger buildings Limited number of printing methods and tailored concrete mixture design

of new biomedical implants, engineered tissues and organs, and controlled drug delivery systems [158]. AM flexibility allows for manufacturing extremely complex shapes by engineering novel materials such as semi-crystalline polymeric composites [159].

- *Customisation and patient-specific necessities*. Biomedical applications need to be patient-specific, from implants to drug dosage. AM presents great potential for patient-specific biomedical products, from hearing aids to biomedical implants [160] and from customised orthotics to prostheses [161]. AM is also used for planning surgeries [162], improving efficiency and effectiveness, and reducing the necessity of further operations to adapt the implant to the patient. AM will also be used for customizing drug dosage forms and releasing profiles [163].
- *Small production quantities.* AM is more cost-effective compared to traditional manufacturing methods for lower production volumes, which are typical in the biomedical industry. Moreover, it allows for manufacturing complex products without the necessity of preparing new tooling fixtures each time. AM can prototype parts faster than conventional manufacturing methods, such as moulding, forging and milling in a fraction of the time [164].
- *Easy public access.* AM CAD files can be easily shared among researchers to reproduce the same design. For example, the project 3D Print Exchange for sharing AM files freely has been initiated by the National Institutes of Health (NIH) [165].

Biofabrication involves the generation of tissues and organs through bioprinting, bio-assembly and maturation [166,167]. The main difference between biofabrication and conventional AM is the inclusion of cells with the manufactured biomaterials for producing the so-called bio-inks [168]. Bioprinting with bio-inks is integrated with the laser-induced forward transfer (LiFT), inkjet printing and robotic dispensing [167]. These specialised techniques are well discussed in the literature [169]. The biomaterials combined with biomolecules and cells are then matured in the desired shape and tissue. The biomaterials are used as support and physical cues for the generation of the tissue structure while the biomolecules guide the tissue regeneration process. Multiple bio-inks and cells will be combined with more complex tissues and organs. Advanced imaging will make it possible to obtain the precise shape, size and composition of defective parts. Moreover, using autologous cells from the patient will reduce the risk of rejection of the generated organ/tissue. The manufacturing of cartilage [170], bone [171], aortic valves, branched vascular trees [169] and bioresorbable tracheal splints [172] have been conducted *in vitro* or *in vivo*. *In situ* generation of tissues to repair organs and tissues directly in the body is another important goal of bio-fabrication, which has already been achieved with skin [173], bone [174] and cartilage [175] to some extent. Bio-fabricated parts will also be used as models for toxicity tests, disease models [176] and for testing adverse reactions to drugs, even in a patient-specific manner [177].

There exist limitations in current bioprinting techniques because of the requirement of working with fragile cells. For example, the pressure used to expel the bio-ink from microextrusion bioprinters must be low enough in order to not distort the cellular structures and damage cells. High extrusion pressures can reduce the number of usable cells by up to 40% [178]. Inkjet bioprinting uses high temperatures during manufacturing (up to 300 °C in the nozzle) but the high temperature does not damage the cells because the localised heating lasts for only ~2 μs and it increases the local temperature only between 4 °C and 10 °C [179]. A more critical issue is the choice of bio-ink scaffolds. In particular, cells must remain attached to the scaffolds and guarantee adequate protection from mechanical and thermal stresses at the same time. Moreover, they must drive the desired cellular growth and proliferation without the development of unwanted cell types [180]. The used material must be cytocompatible, so it does not trigger immune and inflammatory responses, and premature stem cell differentiation [181]. Many bio-ink scaffolds have been developed to address the aforementioned issues but limitations still exist in the optimum 3D printing of biomaterials [182].

A grand challenge in bio-fabrication is the development of vascularized organs [167]. As large organs need blood vessels to continue their metabolic functions, it will be necessary to develop methods to create complex vascular systems and innervation. Zhang et al. [183] reviewed recent progress in 3D bio-printing of blood vessels and functional vascularized tissue. The current limitation to printing at fine resolutions at a miniature scale, as well as the lack of available mechanical properties for vascularized tissues, suggest further research and development in this area in order to fabricate 3D printed tissues. However, versatile bio-ink developments in recent years remark the potential of additive manufacturing in tissue engineering of delicate human parts. Bioreactors are being studied together with factors that promote angiogenesis and innervation to mature bio-printed parts with the necessary characteristics [184]. The combination of different bio-inks and AM techniques is showing positive results for the creation of human-scale tissue constructs (Fig. 6) [185]. Also *in situ* bio-printing for the regeneration of tissues is an advanced paradigm that will change

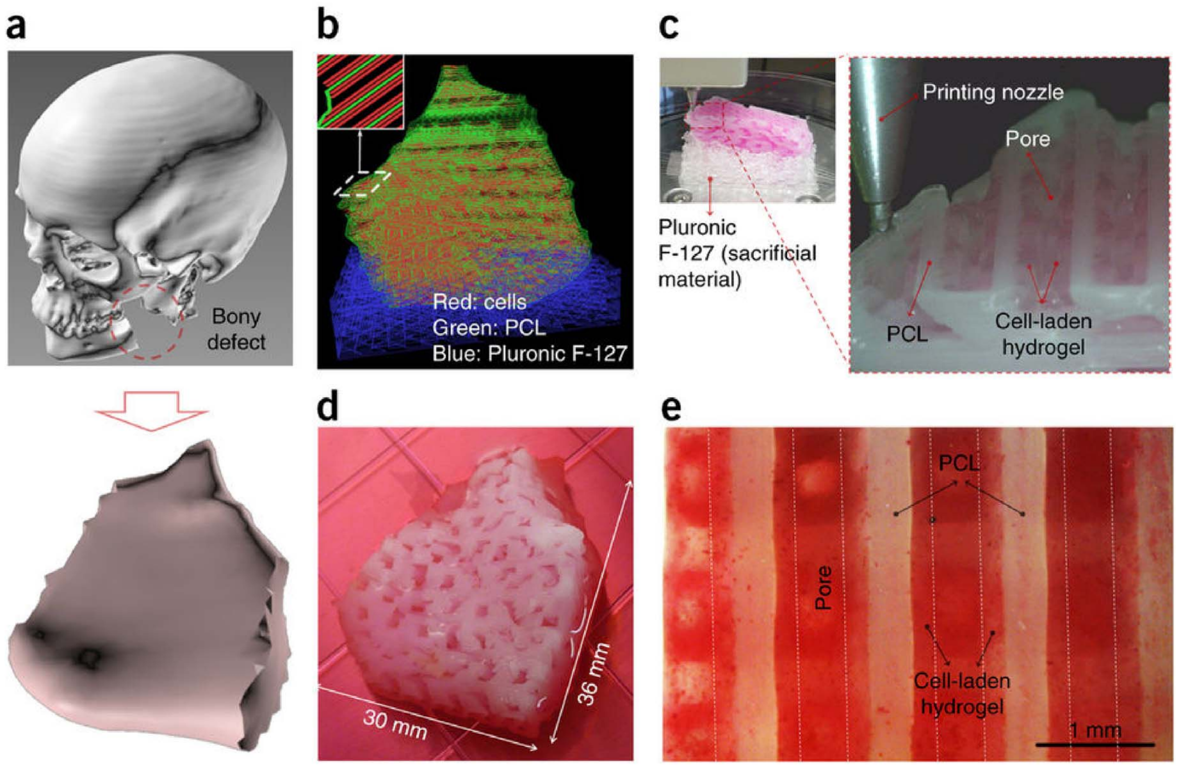

Fig. 6. (a) a 3D CAD model individuates a defect in the mandible from CT scan images; (b) Motion distribution of print from the developed software. Green, blue and red indicates the paths of PCL, Pluronic F-127 and hydrogel, respectively; (c) AM process; (d) 3D printed bony defect implant, cultured in osteogenic medium for 28 days; (e) Osteogenic differentiation confirmed by Alizarin Red S staining, showing calcium deposition (Courtesy of Kang et al. [185]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the biomedical industry.

The pharmaceutical industry will receive great benefit from AM. Therefore, drug manufacturing and delivery systems will change radically. The Food and Drug Administration (FDA) already approved the first AM drug in 2015 [163].

Novel AM drug delivery systems are being developed: solid dosage forms (the most studied for its easy commercialisation) [186]; implantable drug delivery vehicles [187]; and topical drug delivery systems [188]. AM could control the release profile of drugs by changing the 3D shape [186], micro-architecture of drug delivery systems, and as well as the position of the active agents [189]. Novel dosage forms have been created using AM, such as microcapsules, antibiotic micro-patterns, synthetic extracellular matrices, mesoporous bioactive glass scaffolds, nano-suspensions and multilayered drug delivery devices [190].

It will be possible to manufacture personalised medicines on-demand, both for dosages and for special pharmacogenetic profiles. Factors such as age, race or gender could be used to fabricate the most effective medicine [190]. More drugs could be combined in one tablet, with controlled release of the individual drugs [190]. Another on-demand application will be the additive manufacturing of unstable drugs with a limited shelf-life [163]. Different active ingredients have been studied, such as steroidal anti-inflammatory drugs, acetaminophen, theophylline, caffeine and others [190]. Computational models could help to predict the release profile of AM delivery drug systems [191]: the effects of geometrical design, microarchitecture and disposition of active and passive agents, and their release profiles need to be investigated.

AM is also changing the implant industry i.e., it is now possible to develop patient-specific implants [192]. Nowadays, development pipelines include the image acquisition of the body part, its elaboration, the implant design and manufacturing, all using computer-aided design (CAD) software [166]. Anatomically complex geometries can be manufactured quickly by a reliable and cost-effective AM method. Patient-specific AM implants are already available but most of them have been only used in trials, with explicit authorisation from the patient [193]. In the future, consistency of the processes and materials will be fundamental for definitive approval from the regulatory authorities.

Complex geometrical features can also be implemented in implants. For example, lattice structures with low stiffness and high strength are being studied to eliminate (or reduce) stress-shielding between the implant and the bone [194]. Some lattice structures can be inspired by biomimetics [195]. The freeform possibilities of AM allow for integrating this mechanical function with the optimisation of other factors such as tissue ingrowth, osseointegration, transport of nutrients, waste and antibiotics, biocompatibility, and bioresorbability [196]. Lattices with graded structures could also change the local properties, thereby optimising the implant behaviour [197]. For example, the lattice can present higher stiffness internally to sustain higher loads and higher porosity externally to help with bone ingrowth.

Biocompatible titanium alloys and biodegradable materials (both polymer-based and metal-based materials) have been tested *in vitro* and *in vivo*. Ti6Al4V lattice structures are very promising both mechanically and for bone tissue growth. Biodegradable materials are developed as, in certain clinical cases, the material support, which is only temporarily necessary to support the growth and healing process. Mg stents and screws showed good mechanical and degradation response, with no negative body reactions or inflammation [198].

The development of numerical methods to design and incorporate complex geometrical features in the implants will facilitate the design of the macro-scale shapes and micro-architecture [192]. AM has been used for prosthetics and orthotics, allowing customisations for both fitting the patient's anatomy and improving functional aspects [199]. Both high-end and low-end market devices are being developed. High-end market devices are developed to improve aesthetics, functionality and comfort. Low-cost devices present the simplified design and can be manufactured in developing countries at a fraction of normal costs. Many solutions have been proposed in the literature [200,201]. High-end market devices are driving the development of functionalities and improved AM techniques. At the same time, studies are being conducted to manufacture devices that are easy to adapt, manufacture and assemble for people with inadequate health care.

AM has been already used in the biomedical industry and will be a protagonist in the future. However, some challenges must be addressed:

- *Regulatory issues.* AM biomedical products require FDA approval [202]. The biomedical industry is currently concentrating on Class I devices, which require less efforts to be approved. However, the development of Class II and III devices is continuing, with the approval of some Class II implants [203];
- *Limited materials.* Traditional biomaterials can often not be 3D printed, while the best performing AM materials are not biocompatible [166]. Thus, the development of novel techniques and materials is important;
- *Inconsistent quality.* The mechanical properties of AM materials have not been properly characterised [204]. AM materials and the process parameters can greatly affect the final properties

Future trends will concentrate on the development of:

- *On-demand and patient-specific applications.* The development of automatic methods to combine CT-scan results and design analyses with AM technologies will allow for manufacturing patient-specific implants quickly [164]. Moreover, the development of drugs and drug delivery systems will be based on the necessities and characteristics of the patient [190];
- *Complex parts.* Mechanical properties, cell attachment and growth, transport of nutrients, waste and antibiotics, biocompatibility and bioresorbability are some of the important factors for a biomedical implant [192]. AM could optimise these properties simultaneously with novel designs. Functional composites such as metallic implants coated with ceramic coatings can be developed with advanced functionalities and efficiency;
- *Bio-printing and in-situ printing.* Research and development may help to upscale bio-printed scaffolds and tissues for clinical applications and to improve the cost-effectiveness of AM for tissue engineering. *In-situ* repair of organs and tissues would become possible in the future [205]. Studies for manufacturing AM artificial organs, including vascularisation, innervation and accomplishing the multi-functionality provided by each organ are ongoing [192]. These organs will likely be coupled with electronic devices (cyborg organs) such as the bionic ear, which was used as an inductive coil to receive electromagnetic signals for hearing [206].

4.2. Aerospace

The Wohlers' report [33] shows that the aerospace industry accounts for 18.2% of the total AM market today and is considered one of the most promising fields in the future.

AM techniques are ideal for aerospace components as they have the following peculiar characteristics:

- *Complex geometry.* Complex shapes are necessary for integrated functions i.e., structural, heat dissipation and airflow. For example, GE Aviation is developing fan blade edges with optimised airflow [207]. Moreover, it is possible to simplify parts by combining multiple components, such as GE fuel nozzles [208]. Finally, functional electronics can be implemented (or printed) easily as AM parts [209];
- *Difficult-to-machine materials and high buy-to-fly ratio.* The aerospace industry uses advanced and costly materials, such as titanium alloys, nickel-based superalloys, high-strength steel alloys or ultra-high-temperature ceramics that are very difficult to manufacture and create a large amount of waste materials (up to 95%) [210]. AM reduces waste (down to around 10–20%) [211] and provides complex shapes;
- *Customised production.* The aerospace industry is characterised by the production of small batches of parts. AM is more convenient economically than conventional techniques for small batches as it does not require expensive equipment such as molds or dies;
- *On-demand manufacturing.* Airplanes have a long working life of up to 30 years. Keeping old parts incurs a notable cost of inventory [212] but AM is capable of manufacturing parts on demand, thereby reducing the maintenance time;
- *High-performance to weight ratio.* Aerospace components need to be lightweight and present high strength- and stiffness-to-weight ratios to reduce costs and emissions. For example, the cost of space travel to Low Earth Orbit (LEO) i.e., orbit around Earth at an altitude of 2000 km is around $2500 per kg [213].

Both metallic and non-metallic (such as metamaterials [215,216]) parts for aerospace applications can be manufactured or repaired using AM such as aero engine components, turbine blades and heat exchangers. Non-metal AM methods such as stereolithography, multi-jet modelling [217] and fused deposition modelling (FDM) are used for the rapid prototyping of parts and for manufacturing fixtures and interiors made of plastics, ceramics and composite materials.

DED technology is used for manufacturing large structural components as it is less accurate than PBF ($\pm$ 1 mm accuracy versus $\pm$ 0.05 mm) but much quicker (up to 10 times) [24]. For example, 'Norsk Titanium AS' manufactures titanium structural parts for the Boeing 787 Dreamliner using their in-house 'Rapid Plasma Deposition™' process in which a titanium wire is melted in a chamber filled with argon gas [218]. This method resulted in a reduction of cost by $2 to $3 million per aircraft [219]. 'Thales Alenia Space' in collaboration with 'Norsk Titanium AS' were able to reduce the buy-to-fly ratio in half with a lead-time reduced by six months [220]. 'GKN Aerospace' developed the first advanced 'Ariane 6 nozzle (SWAN)' for the 'Vulcan 2.1' engine produced by 'Airbus Safran Launchers' (see Fig. 7a) [221]. Large-scale DED allowed the production of the 2.5 m diameter nozzle, which reduced the number of parts (from ~1000 to ~100), costs (~40%) and production times (~30%).

The high precision of powder bed fusion (PBF) technologies allows for the optimisation of component design and integration with other functions. This technique is used mainly for smaller parts with higher complexity. The brackets developed for the Airbus A350 XWB are 30% lighter and reduced the manufacturing time by about 75% (see Fig. 7b) [224]. Arconic manufactures titanium fuselage and engine pylon components for the Airbus A350 XWB and A320 test versions [225] and NASA's SLS/Orion spacecraft vents [226]. GE Aviation is using metal PBF machines to manufacture its next-generation of jet engine components, which are characterised by intricate shapes for better cooling pathways and supports [227]. The service life was incremented five times the number of required parts was reduced from 18 to 1, and the weight was reduced by 25%.

Non-metallic parts are also important for the aerospace industry. Plastics, ceramics and composites can be manufactured through stereolithography, multi-jet printing and FDM processes. Stratasys [228] adopted FDM for rapid prototyping, manufacturing tooling and part production in collaboration with various aerospace companies, such as Piper Aircraft, Bell Helicopter and NASA. For example, NASA printed 70 components of the Mars rover using Stratasys FDM technologies to obtain a lightweight and strong structure [229]. Bell Helicopter manufactured polycarbonate wiring conduits for their V-22 Osprey using FDM [230] whilst reducing the manufacturing time to 2.5 days (from 6 weeks).

The NASA Aeronautics Research Institute is trying to develop an AM non-metallic gas turbine engine [231]. Lightweight and high-

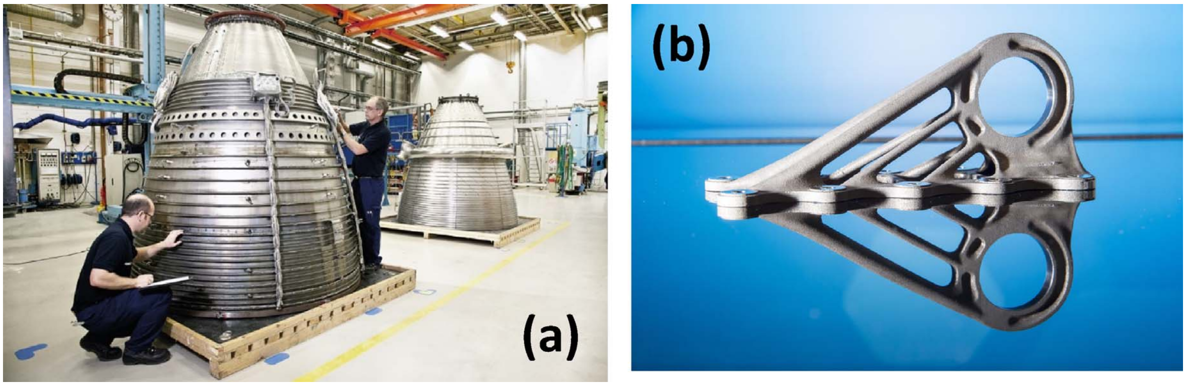

Fig. 7. (a) In the foreground, Vulcain 2 demonstration nozzle with more than 50 kg of DED material [222]; (b) AM Titanium brackets for AW350 XWB [223].

temperature resistant composite materials are being explored. Polymer matrix, polyetherimide and ceramic matrix composites were produced with FDM and binder-jet processes. AM of ultra-high-temperature ceramics (such as ZrB2, ZrC, TiC and others) is currently an important area of study [232].

High-performance aerospace components are made of expensive materials with advanced and complex manufacturing techniques [233]. These parts are also subjected to corrosion, impacts, stress and repeated thermal cycles that can generate defects or cracks. As these parts are extremely expensive, replacement is more favourable than repair. On the other hand, AM technologies can repair high-value metal components with high precision and little generation of heat compared to conventional welding processes [234]. A laser beam creates metallurgical bonds between the part (i.e., the substrate) and the added repair metal (i.e., the powder). This technique generates minimal distortions and can be used for complex and thin-walled aerospace parts. Also "non-weldable" materials or distortion sensitive parts can be repaired with AM [235].

In the most common approach, DED machines spread and melt metal powder on the damaged area, while CNC milling machines improve the quality of the repair. Greater build capability, better accuracy and better surface finishing can be achieved by this method [236]. The added material presents better fatigue properties than the original wrought material with no distortion beyond dimensional limits [237]. Moreover, this technique minimises the degradation of mechanical properties caused by thermal stresses and can virtually repair any damage, even in non-visible zones [238]. The cost for repair has been evaluated at 50% of the cost of remanufacturing the part [237]. Automatic systems are being developed to individuate the damage, align the original CAD files with the physical system (to evaluate the location for adding material) and repair the damaged components with AM and CNC machines [239]. The European Commission sponsored the project REPAIR [240] to develop a semi-automated system for monitoring, analysing and repairing defects. This system should reduce the cost of complex spare parts by 30%, their turnaround time by 20%, the production of scrap and toxic chemicals by 80%, the component weight by 20%, and the inspection time by 30%.

AM will also change the spare parts supply chains [241]. The distributed production of spare parts will reduce the overall operating costs and downtime, as well as limiting inventory management and logistics information systems. At the same time, AM will increase customer satisfaction, flexibility, capacity and robustness against supply chain disruptions. However, these changes would happen if the costs of AM machines and raw materials decrease. AM can also manufacture older parts without keeping old tooling systems, molds and dies. For example, repairing and updating F-15 aircrafts using AM with substantial cost savings has been done [242].

AM technologies already demonstrated great capabilities, from rapid prototyping to the manufacturing of end-user parts, as well as semi-automatic repairing. The aerospace industry is capable of driving further evolution [211] whilst trying to overcome some limitations:

- *Size of the parts.* DED technologies can manufacture parts with a maximum height of 5.79 m [243]. Therefore, large-scale parts need novel approaches to relieve internal stresses and consequent distortions e.g. ultrasonic tools [244];
- *Scalability.* It will be possible to use AM for mass production. However, the cost reduction is necessary for both the machines and the raw material before it becomes a feasible scenario [245];
- *Limited material and high cost.* The cost of additive manufactured material per weight is higher than that of conventionally manufactured materials [246]. However, the lower buy-to-fly cost of AM parts (with nearly no waste compared to a large amount of waste material generated from conventional manufacturing of titanium brackets [247]) contains this issue for some applications. The number of AM materials is limited but new AM-adapted materials are being developed e.g. strong aluminium alloys [83], ultra-high-strength ceramics [21] and ceramic-matrix composites [248].
- *Inconsistent Quality.* AM allows the manufacturing of complex structures but their mechanical properties have not been properly characterised [204]. In powder bed fusion, the manufacturing process and its parameters greatly affect the material properties and can increase porosity and induce thermal stresses. Methods for process monitoring and the creation of process-structure-property relationships integrated with CAD tools are fundamental to detect and predict defects in order to improve the final design [249].

Future work will concentrate on the development of:

- *Multifunctional structures.* The possibility of manufacturing complex parts with multiple functions enhances the design freedom and allows for innovative solutions. AM eliminates (or substantially reduces) the necessities of assembly and connections, the necessity of fixtures and tools, and saves weight and material [250]. Moreover, it is possible to integrate sensors, circuits (printed with conductive inks) and wiring [251] or combine thermal and acoustic insulation functions in the structure [214].
- *Ceramics.* Ceramic materials are frequently used for space flight, which are required to perform at elevated temperatures. Ceramics can also be used in piezoelectric devices. However, their shapes are limited by conventional manufacturing processes. AM of ultra-high-strength ceramics is also being studied [21].
- *Functionally Graded Materials.* Materials produced with AM techniques could be combined to tailor the mechanical and thermal response of components. A combination of metals and ceramics would reduce the brittleness of the ceramic thermal shield used during re-entry into the Earth's atmosphere [252]. However, the combination of multiple alloys will require the development of computational

phase diagrams and the evaluation of material compatibilities [253].

- *On-demand Manufacturing.* AM produces components on demand, reduces storage costs and eliminates the possibility of damage during storage [254]. For example, AM is being tested on the International Space Station [255] and could be used for manufacturing a Moon village [256].
- *Automated repair processes.* The use of repairing processes is reducing the costs of high-value components during their lifetime. However, it is necessary to develop automatic methods to detect defects and automate repair processes. The European project RepAIR [240] and other studies funded by GKN Aerospace [239] are attempting to address these issues correctly.

4.3. Buildings

Wohlers' report [33] shows that the architectural applications represent only 3% of the total AM industry. However, this sector is in its infancy as it started to be used for residential structures only from 2014 [257] and has shown great potential since then. Automated building construction with 3D printing technology has gained increasing attention in recent years. It can potentially revolutionize the construction industry and it can offer astronauts easier construction on the moon [258]. It offers a significant reduction in construction time and manpower [3]. The traditional techniques used in the construction industry are casting, moulding and extrusion. The use of 3D printing in the building industry can be utilised in areas where there are constraints, such as geometric complexities and hollow structures. Hence, its reliability is due to its ability to fabricate with high precision and opens up various design possibilities. Khoshnevis [19] developed the contour crafting (CC) technology for the automated construction of buildings and infrastructure, and for space applications. Due to its ability to utilise in-situ materials, it can be readily used for the construction of low-income housing and for building shelters on the moon. The first 3D printed residential structure was developed in Amsterdam in 2014, where the FDM method was utilised (Fig. 8a) [257]. The project was pushed through by architects from Dus Architects, who wanted to demonstrate the mobility of the printer with minimal material wastage and transportation costs, thereby paving its path to the building industry. It was also in 2014 when WinSun, an architectural firm in China, mass printed residential houses in Shanghai in less than 24 h (Fig. 8b) [3]. Traditional 3D printers restricted the use of this technology in the industry due to its size. However, a 3D printer with a size of 150 m (L) x 10 m (W) x 6.6 m (H) was employed in this project, which used cement and glass fibre. Some of the challenges encountered by WinSun throughout the duration of the project include problems with brittleness, integration of building services and indirect printing [3].

Lim et al. [259] described three large-scale 3D printing techniques that are suitable for the construction industry, which differ based on the materials utilised and the application process. D-shape and concrete printings are both frame-mounted and gantry-based, and the manufacturing process is typically done off-site. On the other hand, the contour crafting technique, which is robot or crane-mounted can be also used for on-site applications. Nadal [260] also summarised the techniques used to scale up typical desktop 3D printing into two main methods: 1) bridge crane approaches and 2) methods comparable to CC. However, some difficulties are encountered when these methods are conducted off-site, such as material wastage and imprecisions that tend to be more labour-intensive [260]. Hager et al. [261] used a promising technique similar to CC technology which uses cementitious materials, thermoplastics and ceramic products, which can transform the construction industry in the future. CC technology has the ability to print layers on-site, thereby enabling the printing of large components with unlimited flexibility and precision. The material used for the first on-site CC construction was a mixture of cement and sand. CC is also commonly known as the first feasible AM technique for building construction. The D-shape method, on the other hand, utilises the powder deposition process where a chemical agent, such as a chlorine-based liquid, is used to bind the powder (e.g., sand or stone powder). The process results in structural parts with good mechanical properties. However, the control instructions and increase in required maintenance remain to be the major hurdles of this technique [262]. The potential for utilising D-shape printing method in harsh spatial environments and making use of its local resources was also investigated by Cesaretti et al. [263].

The possibility of building infrastructure on the Moon with the use of lunar soil (regolith) and the application of D-shape printing were assessed. With the design requirements of the outpost identified, a preliminary design of the habitat has been developed. One of the crucial aspects of using 3D printing involves the capability of the material to withstand the lunar environment. Labeaga-Martínez et al. [258] recently reviewed the use of AM in the proposed Moon Village of the European Space Agency. Lunar regolith was also the raw material to be used with the various AM technologies that were assessed. Powder bed fusion was deemed to be the appropriate and feasible technology for the mission.

Another technique developed by Loughborough University is mesh-moulding, which utilises a six-axis robot control to manufacture elements without temporary support. The mesh-mould technique also utilises thermoplastic polymers where the printed structure also acts as reinforcement for concrete. After the concrete is poured, it is trowelled manually to make the surface smooth. This technique is particularly useful in constructing complex structures, which can significantly reduce the time needed for fabrication. Furthermore, the density of the printed mesh can vary depending on the forces that will act upon the structure. The possibility of replacing steel reinforcement is also reported as the presence of a mesh in the structure helps to increase the tensile strength of the concrete [264]. Although Lim et al. [259] reported concrete printing to be an off-site process, they also stated that

Fig. 8. (a) First 3D printed house by DusArchitects [257]; (b) 3D printed house by WinSun [3].

appropriate modifications could lead to on-site manufacturing processes. In recent years, four-axis gantry and six-axis robot are the types of printers already used for concrete 3D printing.

3D printing has also become a vital process for cultural preservation and reproduction. Xu et al. [265] developed a process for reproducing a component of a historic structure where 3D scanning was integrated with cement mortar-based 3D printing. Utilising this technology resulted in cost-effective and labour-efficient construction as compared to traditional methods. Sobotka and Pacewicz [266] analysed the different impacts of using 3D printers on-site, particularly in difficult conditions, and employed the strengths, weaknesses, opportunities and threats (SWOT) analysis to characterize this technology. The researchers have identified that this technology can provide opportunities for low demand for heavy machinery, construction equipment and the possibility of using recycled materials. Stoof and Pickering [267] developed a sustainable composite for FDM printing using a recycled polypropylene (PP).

Since raw materials and manufacturing process using 3D printing are distinct from conventional construction methods, the necessity for skilled workers with the ability to incorporate both robotic and civil work together remains another hurdle for AM in the construction industry [264]. The construction industry is considered to be responsible for consuming one-third of the Earth's resources. Hence, material efficiency and effective construction strategies are both important factors for addressing environmental impacts. To increase the applicability of 3D printing in a large-scale construction project, it is best to understand the technology thoroughly for it to be utilised to its full potential. In particular, fabrication of lightweight concrete composites [268–270] with customised pore size distribution as well as freedom of mix design of geopolymer concrete [271] are interesting concepts for the further development of AM in the future. Although the AM technology is still in its infancy in the construction industry, it can be seen that traditional building processes can potentially be improved by utilising this technology. Further research is expected to explore and develop this technology, which will result in more opportunities and increasing challenges arising in the building industry.

4.4. Protective structures

AM is allowing for a rapid evolution of protective structures, from the analyses of sandwich panels filled with the most disparate lattice cores to novel snap-through concepts. Solid monolithic plates made of high-strength steel or aluminium are used for protecting armoured vehicles, while stochastic foams are used for personal protective applications. However, these plates are heavy and expensive. At the same time, stochastic foams are often not optimised for a particular protective application and present irregular responses to loading. Thus, developments in AM and material production technologies are driving the evolution towards smart and lightweight structures with high stiffness-to-weight and high strength-to-weight ratios. This augments economic efficiency (with the potential of AM cost reduction in the future) by reducing weight (increases mobility and safety for military vehicles), thereby increasing the efficiency of the protective system. Nature-inspired composite structures have been developed with AM, which can withstand the impulsive energy of impact or blast. A novel design of a voronoi-based multi-layer composite structure demonstrated significant energy dissipation under impulsive loading compared to an equivalent monolithic panel of equal mass due to well-distributed damage in cohesive and inter-laminar adhesive bonds between nacre-like aluminium tablets [272].

AM technologies are also being used for manufacturing lattice structures [273]. In general, cellular materials are characterised by large densification strains, high specific strength and the possibility to have a uniform and smooth plateau stress during loading. Thus, they have been thoroughly analysed for energy absorption applications [274,275]. In particular, AM lattice structures are characterised by:

- *Freedom* of *Design.* AM allows for manufacturing extremely complex geometries from beam-based lattices, such as body-centred cubic (BCC), to surface-based lattices, such as gyroids. The structures can be small (a few micrometres) or large (a few metres). Many different responses can be induced, from conventional stretching- and bending-dominated behaviours to snap-through mechanisms. Moreover, it is possible to combine more materials into a single structure, for increasing ductility or stiffness. This freedom facilitates parametric (based on the variation of geometric parameters) and topological optimisation to obtain better responses than conventional metallic foams [276].
- *Uniformity and repeatability in the response.* Lattice structures are manufactured with a precise shape, such that they have a consistent response to impulsive loads. The evolution of AM technologies resulted in a reduction of defects in the manufacturing of smaller parts.
- *Multi-functional.* The main advantage of AM is design freedom from manufacturing constraints. Thus, it is possible to create shapes for optimising multiple functions simultaneously. In particular, lattice structures for protective purposes are being optimised for thermal applications (e.g. thermal shields for Earth re-entry from space [277] and heat exchangers [278]). Acoustic applications such as sound insulation or sound cloaking can also be optimised with the help of AM.

Most of the lattice structures used for energy absorption are made of metal alloys but recent studies are evaluating polymers, such as silicone and rubber-like materials. In particular, metallic lattice structures dissipate mechanical energy using plastic deformation, while novel methods try to absorb energy in the form of elastic deformation using bistable structures [279]. Studies on metallic lattice structures evaluated different unit cell topologies, such as BCC and its derivatives [275,280], lattice-walled honeycomb (LWH) [281] and gyroids [282] among others (Fig. 9). Also, the effect of different materials (TiAl6V4 [283,284], SS316L [275,281,283] and AlSi10 Mg [285]) has been studied.

Variation of the lattice topology changes the response of the lattice structure, from the bending-to stretching-dominated behaviour. Therefore, it is possible to finely tune the behaviour of a metallic lattice structure against impulsive loads. For example, LWHs showed higher energy absorption properties [281], while triply periodic minimal surface gyroids presented lower stiffness and higher strength than other lattices [282,286]. These studies also showed that it is necessary to use a proper material for optimising the response. As-manufactured AlSi10 Mg [285] and Ti6Al4V [283] are extremely brittle and reduce the effectiveness of lattice response. Thus, it is necessary to apply thermal [285] or hot isostatic pressing [283] treatments to increase ductility (at the expense of strength) and obtain a more regular response.

The impact energy absorption of AM polymer lattices has also been discussed by Yin et al. [287] and Craddock [288]. In particular, Craddock [288] studied various lattice topologies and showed that helical struts can absorb more energy than straight struts.

Practical applications of these polymer lattices were developed by different researchers and industries for the Head Health Challenge [289] organised by General Electrics (GE) and the National Football League (NFL) for improving the safety of NFL players on the football field. In particular, the best helmet for protection from the impact was prototyped using AM techniques [290].

Advanced AM technologies, such as direct ink writing, realised innovative structures and exploited innovative energy absorption concepts using different polymers. For example, Duoss et al. [291] used direct ink writing to develop a cellular architecture with negative stiffness. They overlapped sub-millimetre struts of polymeric material with different patterned layouts: "simple cubic" (SC) and "face-centred tetragonal" configurations were realised. These structures could be

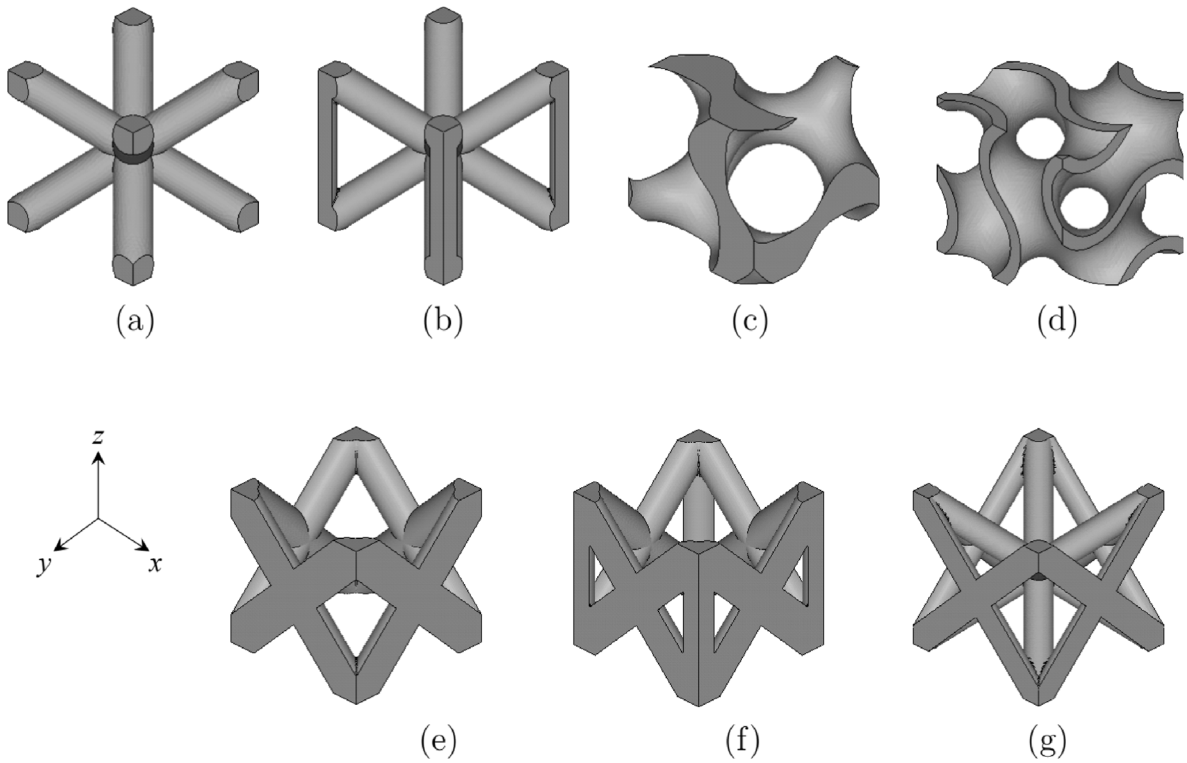

Fig. 9. Seven lattice topologies: (a) body-centred cube (BCC); (b) body-centred cube with vertical struts (BCCz), (c) gyroid, (d) matrix phase of D-gyroid, (e) face centred cube (FCC), (f) face centred cube with vertical struts (PFCC), (g) Boolean combination of BCC and FCC (F2BCC) (courtesy of Maskery and Tuck [286]).

finely tuned to obtain extreme properties, such as negative shear stiffness (SC structures). The developed mechanisms could be used as absorption devices. In particular, these structures snap suddenly at a certain (tuneable) load, which lowers stresses and reduces reaction forces on protected elements. Once the SC structure is unloaded, it would return to its original undeformed configuration.

Direct ink writing has been also used to explore multi-stable structures. In particular, the possibility of using a snap-through concept (i.e., sudden change of geometry caused by instabilities such as buckling) to absorb the energy in a controlled manner has been analysed. Shan et al. [279] developed systems composed of a large number of bistable elastic beams that trap energy using the (reversible) change in state of beams (Fig. 10a). This mechanism depends only on the elastic and geometric properties of the 3D printed systems. Thus, it is reversible and independent of scale, rate and loading history. Moreover, it is easily tuneable for different applications and necessities. A similar concept with multiple configurations has been developed by Restrepo et al. [293]. AM metallic lattice structures are multi-functional. In particular, the combination of managing heat and absorbing impact is of particular interest for the automotive, aerospace and defence industries. Studies have shown that the possibility of developing multi-functional heat exchangers [278] or de-icing systems [294] with good resistance to impact and crash, but commercial applications using AM are also being developed. For example, Magna Parva and MTC manufactured and tested various AM metallic lattice structures to develop a crushable material to be used within an Earth Return Capsule (ERC) for the European Space Agency (ESA) (Fig. 10b) [277]. The crushable structure needed to have low density, low thermal conductivity and be able to absorb high amounts of energy. The use of AM metallic lattice structures allowed for the optimisation of all these conditions contemporarily.

AM is allowing for great advances in the development of novel protective systems. Many lattice structures and innovative solutions have been developed and presented excellent results but some

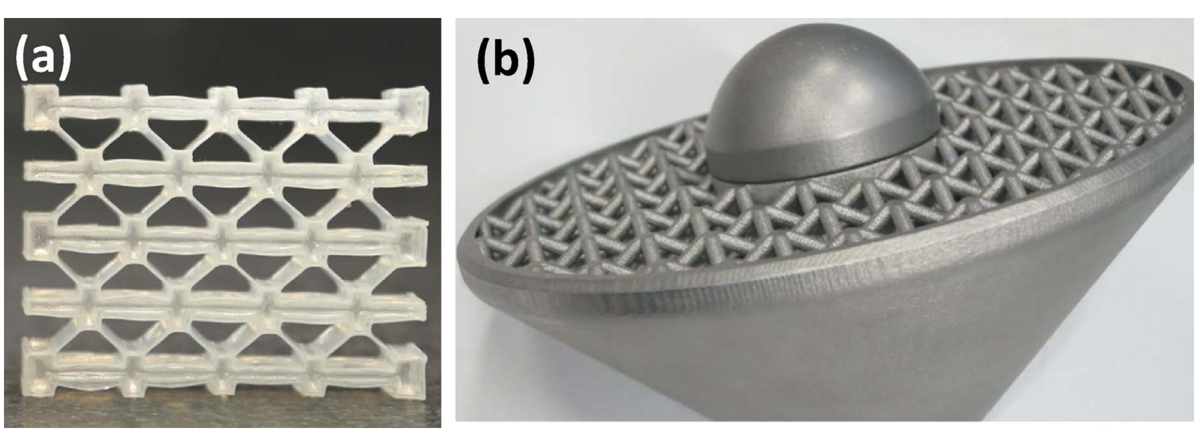

Fig. 10. (a) 3D printed multi-stable architected structure (courtesy of Shan et al. [279]); (b) Additive manufactured protective structure for Mars specimens re-entering Earth from Mars courtesy of Magna Parva [292]).

improvements are necessary. Advanced metal AM techniques have a high precision (± 0.02 mm) but defects and porosity reduce the effectiveness of smaller elements. Smaller specimens showed a reduction of 20% in yield strength and stiffness compared with standard ASTM specimens [295]. Post-manufacturing treatments, such as heat or chemical treatments, are necessary to recover ductility and adequate properties for impact applications [296].

Future applications and evolutions of additively manufactured lattice structures for protection against impulsive loadings will include:

- Multifunctional performance. Current studies and commercial applications are already exploring combinations of protective and thermal applications. However, acoustic optimisation could be coupled with bird-impact protection and thermal management for aerospace applications. It will be necessary to develop multi-physics simulations for achieving the best results. Advanced optimisation algorithms and numerical models will be used to maximise the efficiency of the structures in terms of weight [297,298].
- *Novel designs for energy absorption.* Novel concepts can be evaluated quickly using AM e.g. optimised auxetic structures [299–302] or resonators for dynamic load mitigation [303]. Also, the possibility of developing graded structures (graded struts [304] and graded stiffness for robot bodies [305]) paves a path for other innovative solutions. Metallic hollow wall micro-lattice structures can absorb a large amount of energy per unit mass through plastic deformation, local wrinkling and plastic buckling [306]. In particular, they perform better than conventional lattice structures. Studies to improve the quality and to reduce the cost of manufacturing hollow struts [307] can be also of primary importance.
- *Novel materials and composites.* Strong metal alloys (such as Al 7075), commonly used for blast applications, can be now additively manufactured [83], and can thereby result in significant improvements in resilience to impulsive loading. AM of Shape Memory Alloys (SMA) [308] and Shape Memory Materials [309] will open other possibilities too. It will be possible to create lattices that are able to deform and subsequently recover their previous shape with the little external stimulus, and the same initial mechanical properties [310]. Finally, more work could be performed on composites [311] e.g. a softer material in the vicinity of plastic hinges and a stiffer material to improve the resistance of the lattice structure to localised forces.

5. Main challenges

Despite the benefits of 3D printing such as the freedom of design, customisation and the ability to print complex structures, there are a few drawbacks that would require further research and technological development. These drawbacks include high costs, limited applications in large structures and mass production, inferior and anisotropic mechanical properties, limitation of materials and defects. The research and development of materials and methods have helped to circumvent some of these challenges. However, few remaining challenges need to be addressed in order to expand additive manufacturing (AM) to a broader range of applications and industries. Some challenges are more pronounced in a particular printing method or material but few are common in almost all AM methods. For instance, AM of a part typically takes more time compared to traditional methods such as casting, extrusion, fabrication or injection-moulding. In particular, the powder bed method and stereolithography are more time-consuming compared to inkjet printing and fused deposition modelling. In addition, 3D printing methods, such as powder-bed (SLS or SLM), are high in resolution, which thereby incur a higher cost for materials and a higher amount of energy for processing. The long processing time and higher cost of 3D printing are the main challenges that inhibit the mass production of any repetitive parts, which can easily be performed by other conventional methods at a fraction of the time and cost. However, when it comes to a customised product with a complex structure e.g. a 3D printed scaffold for bone tissue engineering, AM can be more cost-effective [312]. Regardless of time and cost of 3D printing production, which should be analysed in each specific application, four main challenges that are attributed to the nature of AM are discussed and compared among the current methods and materials for 3D printing hereafter.

5.1. Void formation

One of the main drawbacks of 3D printing is void formation between subsequent layers of materials. The additional porosity created by AM can be very high and can thereby reduce mechanical performance due to the reduction of interfacial bonding between printed layers [13]. The extent of void formation highly depends on the 3D printing method and the printed material. In the methods that use filaments of materials such as FDM or contour crafting, the formation of voids is more common and considered as one of the main defects that result in inferior and anisotropic mechanical properties [13,148]. This void formation can also result in delamination between layers after printing [146]. In a 3D printed composite using the FDM method, increasing the thickness of the filament decreased the porosity but deteriorated cohesion in the composite, which resulted in a reduction of tensile strength and an increase in water uptake [313]. The increased thickness of concrete layers with more time lapse between subsequent layers resulted in better interlayer bonding and less void formation in the additive manufacturing of concrete. On the other hand, in the powder-bed printing of alumina/glass composite, the high porosity of AM can be reduced substantially by minimising the height of each layer [314]. The reduced height can increase laser penetration through the top layer and promote diffusion of ceramic powders between layers, thereby reducing interlayer void formation. Furthermore, Paul et al. [142] showed that rectangular nozzles result in less voids compared to cylindrical nozzles because of full contact between subsequent layers. However, 3D printing of complex shapes, especially at the joints, is more difficult for rectangular nozzles.

The higher porosity of 3D printed parts is not always a defect and can be exploited in applications for which controlled porosity is considered as an advantage of AM e.g. porous scaffold design in tissue engineering. Minas et al. [130] took advantage of void formation due to the 3D printing process. They introduced larger pores into a lattice structure on top of micro-pores, which were created by air bubbles inside the foam filament. For biocomposites, the higher porosity of the 3D printed part can introduce hygroscopic properties by increasing the ability to retain water [313].

5.2. Anisotropic microstructure and mechanical properties

Anisotropic behaviour is one of the main challenges of AM. Because of the nature of layer-by-layer printing, the microstructure of the material inside each layer is different compared to that of at the boundaries between layers. Anisotropic behaviour results in the different mechanical behaviour of the 3D printed part under vertical tension or compression compared to that in the horizontal direction. In metals and alloys, which are 3D printed by heat fusion (SLS or SLM), the addition of subsequent layers reheats the boundaries of the previous layers, which results in a different grain microstructure and anisotropic behaviour due to thermal gradients [315]. Heat penetration of the laser beam into each layer is an important factor for not only controlling the sintering process but also limiting anisotropic behaviour [316].

The changes in morphology and texture in the transverse (build) direction result in higher tensile strength and ductility compared to the longitudinal direction of 3D printed titanium alloy with the SLM technique [315,317]. This anisotropic behaviour has been observed for alloys, ceramics [316] and polymers [318,319]. For instance, the shape of ceramic particles plays an important role in their orientation along the printing direction and anisotropic behaviour is more prominent

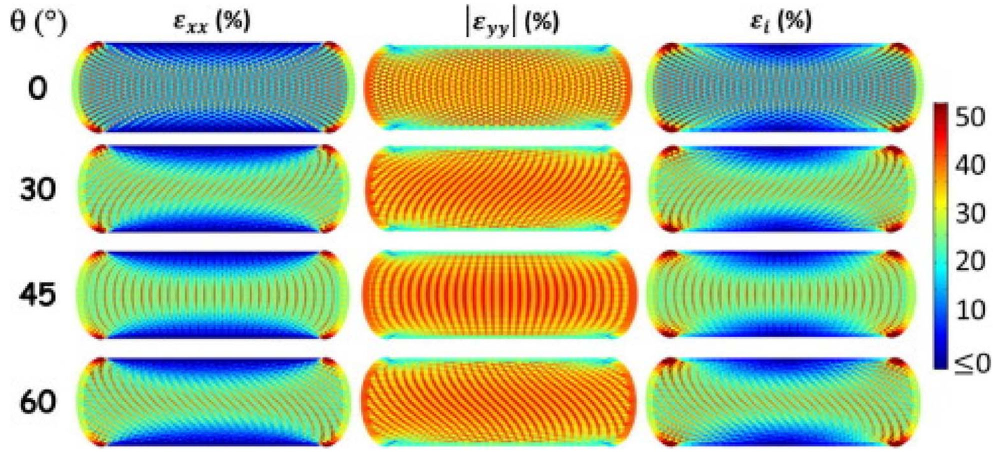

Fig. 11. The strain components at the densification stage as a function of printing angle for ABS 3D-printed polymer (courtesy of Guessasma et al. [319]).

when the shape deviates significantly from a sphere [316]. Fig. 11 illustrates the strain fields at the densification stage as a function of printing angle for ABS 3D-printed polymer [319]. Also, the printing orientation of ABS considerably affects its tensile strength. Zou et al. [320] were able to determine the relationship between printing angle and elastic constants. Printing direction can also affect the mechanical behaviour of nanocomposites [321]. Hambach and Volkmer [144] showed that 3D printing of carbon fibre-reinforced concrete parallel to the length of the beam considerably improves flexural strength compared to a cross-hatch pattern. They also showed that the force can greatly influence the compressive strength of the 3D printed specimens, regardless of whether it is parallel or perpendicular to the printing direction. However, the anisotropic behaviour of 3D-printed materials can be helpful in some applications. For instance, the special anisotropic wettability of a surface can be achieved by controlling the properties of 3D printed filaments (e.g. speed and spacing) on the surface. A super-hydrophobic and anisotropic 3D-printed polydimethylsiloxane film with excellent thermal durability for applications such as breathable water repellent surfaces has been developed [322].

5.3. Divergent from design to execution

Computer-aided design (CAD) software is the main tool to design an part that can be 3D printed. Because of limitations in AM, the printed part can have a few defects that were not expected in the designed element. The CAD system is a combination of solid geometry and boundaries. It typically employs tessellation concepts to approximate the model. However, transferring CAD into a 3D-printed part often results in inaccuracies and defects particularly in curved surfaces [323]. A very fine tessellation can potentially resolve this problem to some extent but the computed processing and printing will be time-consuming and complicated. Therefore post-processing (by heat, laser, chemicals or sanding) to eliminate these defects are sometimes considered.

In order to limit divergence from design to execution, it is necessary to plan and find the optimum orientation of the part, slice the part into sufficient layers and generate supporting materials, which must support the addition of subsequent layers and can easily be removed after printing. The powder-bed method has the advantage of using unbound powder as the support, which can easily be removed by air pressure after printing. On the other hand, FDM, counter crafting and inject printing need to create external support, which is not always easy to remove. Moreover, printing process parameters such as extrusion pressure and orientation of the filaments (in FDM, inkjet and counter crafting), laser power (SLM and SLS), layer thickness, printing direction, temperature and speed of printing, as well as material properties (e.g. rheology, thermoplasticity, powder packing and so on) can greatly influence the appearance and mechanical properties of the 3D printed part [142,324].

5.4. Layer-by-layer appearance

Layer-by-layer appearance is another challenge owing to the nature of additive manufacturing. Fig. 12 shows this defect in a 3D printed concrete structure. The appearance may not be an important factor if the 3D printed part is hidden in the final application e.g. in scaffolds for tissue engineering. However, in other applications such as buildings, toys and aerospace, a flat surface is preferred compared to the layer-by-layer appearance. Chemical or physical post-processing methods such as sintering can reduce this defect [323] but will increase the processing time and cost. Khoshnevis [19] used a trowel-like apparatus attached to the contour crafting print-head to eliminate the layer-by-layer appearance. The thickness of the layer and the height of the part determine the number of layers. Hence, the severity of layer-by-layer appearance can also be limited by reducing the number of layers. The 3D printing methods that use a filament such as FDM, inkjet and contour crafting are more prone to produce a layer-by-layer appearance compared to the powder-bed or stereolithography methods.

6. Conclusions

Freedom of design, mass-customisation and the ability to print complex structures with minimum waste are the main benefits of 3D printing. A comprehensive review of 3D printing methods, materials and the current state in trending applications in various industries was carried out. The main challenges that are attributed to the nature of 3D printing were also discussed.

In terms of methods, fused deposition modelling (FDM) is one of the most common 3D printing technologies because of low-cost, simplicity and high-speed processing. It is originally used for 3D printing of polymer filaments but has been adapted to many other materials. FDM is mainly used for fast prototyping, and the mechanical properties and quality of the printed parts are lower compared to the powder-bed methods such as selective laser sintering (SLS) and selective laser melting (SLM). Adjacent powders are fused, melted or bonded together by using an auxiliary adhesive in Powder-bed methods, which result in finer resolutions but incur higher costs and are slower processes. Direct energy deposition (DED) uses a source of energy (laser or electron beam) to melt metal powders but no powder bed is used compared to SLM and the feedstock is melted before deposition in a layer-by-layer fashion similar to FDM but with an extremely higher amount of energy for melting metals. Inkjet printing is fairly quick and is used for 3D printing of ceramic suspensions but requires post-processing heat treatments. Contour crafting, which relies on extrusion of materials

Fig. 12. The layer-by-layer appearance of 3D printed concrete structure (courtesy of Gosselin et al. [141]).

(concrete), is used to print larger structures such as buildings. Stereolithography is one of the pioneering methods of 3D printing mainly used for photopolymers that can produce parts at a very fine resolution. However, it is a slow and complex procedure that is restricted by a limited number of materials. Finally, laminated object manufacturing (LOM) is based on layer-by-layer cutting and lamination of sheets or rolls of materials.

Materials in the forms of filaments, wire, powder, paste, sheets and inks can be used for 3D printing. Polymers are considered as the most common materials that have been developed for fast prototyping. Polymers such as acrylonitrile-butadiene-styrene (ABS) copolymers, polyamide (PA), polycarbonate (PC) and polylactic acid (PLA), thermosetting powders such as polystyrene, and polyamides and photopolymer resins are the most common type of polymers for 3D printing. The reinforcement of polymers with fibres and nano-materials resulted in enhancing the mechanical properties of the 3D printed composite to be used as a functional material. Metals are mainly in the form of powders (or wires) and SLS, SLM and DED are the main methods of 3D printing. A limited selection of metal and alloys suitable for 3D printing resulted in demands for the adoption of current techniques to a broader range of alloys and composite structures. Ceramics have created a trend to tailor-design materials with a high strength-to-weight ratio and facilitated the creation of complex ceramic lattices for many applications such as ceramic scaffolds for tissue engineering. However, the main challenge is the limited number of available materials for 3D printing of ceramics with better control over the microstructure and composition of the part. Also, mass-customisation, no required formwork and automation are promising for the 3D printing of concrete, although uptake by the construction industry has been slow. A concrete mixture with good flow-ability, process-ability, mechanical performance and appearance has been the main area of recent developments.

Additive manufacturing (AM) substantially contributed to the recent research and development of biomaterials for prototyping complex and customised structures with patient-specific necessities. However, it faces challenges such as limited materials and regulatory issues. The aerospace industry has invested in AM to develop customised parts with higher strength-to-weight ratios, as well as for quick maintenance of aeroplanes and on-demand manufacturing. However, the adoption of AM in the aerospace industry faces challenges such as limited materials and high cost, as well as the inconsistent quality of 3D printed parts. AM technology is still in its infancy in the construction industry with a limited number of successful projects worldwide. The main drawbacks are high cost and reduced mechanical performance compared to traditional methods. However, automation in construction as the result of AM, promises labour-free construction on the moon.

Despite the benefits of additive manufacturing, there are a few drawbacks that would require further research and development to adopt this technology in various industries. Void formation between subsequent layers of materials results in additional porosity during the manufacturing process, which can reduce mechanical performance due to a reduction in interfacial bonding between printed layers. Anisotropic behaviour is another common challenge of AM, which results in different mechanical behaviour under vertical tension or compression compared to that of the horizontal direction. Also, transferring CAD into a 3D-printed part often results in inaccuracies and defects, especially in curved surfaces due to the tessellation concept of CAD, which is an approximation of the design. Moreover, the layer-by-layer appearance of AM in applications such as buildings, toys and aerospace are not preferable. Ongoing research and development of materials and methods have helped to circumvent some of these challenges but there is still room for improvement. Despite being a revolutionary method for customised products and niche applications, 3D printing needs more development in order to compete with traditional methods in the mass production of ordinary goods because of its higher cost and lower speed. Nonetheless, the evolution of AM in recent years has been phenomenal. The increased funding, research and development worldwide would result in a fast transition from traditional methods of manufacturing to 3D printing in the near future.

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