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

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ABSTRACT

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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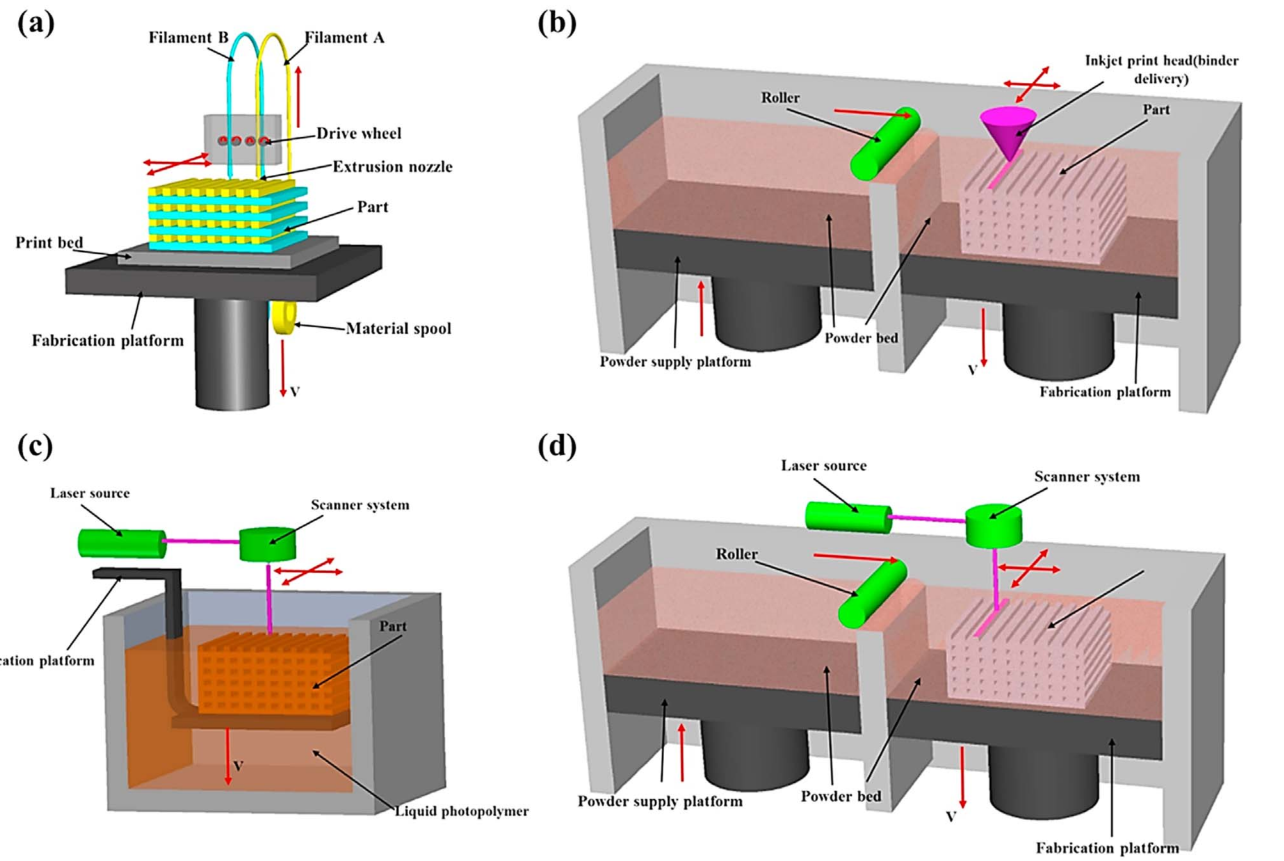

Fig. 1. Schematic diagrams of four main methods of additive manufacturing: (a) fused deposition modelling; (b) inkjet printing; (c) stereolithography; (d) powder bed fusion (courtesy of Wang et al. [13]).

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,

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