3D printed medical parts with different materials using additive manufacturing

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ARTICLE INFO

Keywords:

3D printing
Additive manufacturing (AM)
Customisation
Development
Medical
Materials

ABSTRACT

Background: Identified and studied research articles catering to the medical field on Additive Manufacturing (AM) and its application in different fields using different materials to provide the direction of the development.

Materials and methods: Research objectives are designed to fulfil the research gaps by conducting a literature review based study. Scopus database is used to conduct the bibliometric analysis for different materials as being used in AM towards medical applications. The primary focus is to identify the capability of printing technologies for different materials, thereby providing exclusive benefits to humanity.

Results: We have identified research status on AM and its applications in different fields. By searching keywords as “additive manufacturing”; entire 16043 research articles are identified and by searching for keywords as “additive manufacturing” materials” medical”, 571 research articles are published so far. This paper describes various additive manufacturing processes and twelve primary fields developed by this technology, along with significant references. Finally, identified 16 significant materials being used by AM in the medical field.

Conclusion: Additive manufacturing has the potential to improve the design and development of medical parts and products. This technology is applied for the manufacturing of customised and sophisticated products with different materials, thereby performing it with lesser wastage of time and material. There is a scope to achieve various flexibilities by using different software and technological platforms. AM helps improve the accuracy and reliability of the design, as well as ease of design. This technology is now available for improving the performance of medical part by providing unique and innovative design through the use of different materials with improved quality of the product. This emerging technology provides an extensive capability for future development.

1. Introduction

In the current scenario, additive manufacturing has a high potential through application in various fields. It is flexible with a wide range of material like metal alloys, ceramics, thermoplastics, composites, pure metals that with lower thickness. There is a requirement of exact fit implants using different materials, and AM has a revolutionising effect on the printing of human bone, prosthetics, custom implant, and dental appliances.^{1–3} It shows a high potential for design and modification of the product with the required materials. AM consists of 3D printing, 3D scanning technologies and associated software. It is an automated generation of a physical object from a virtual 3D computer-aided design (CAD) model generated by designing software or by different scanning technologies. This 3D virtual model is converted into standard

triangulate language (STL) file format, which is easily printable by AM technologies using the layer by layer technique.^{2,4}

The major printing technologies used in additive manufacturing are Selective Laser Sintering (SLS), Stereolithography (SLA), Fused Deposition Modelling (FDM), Multijet/Polyjet 3D Printing, Digital Light Processing (DLP), Direct Metal Laser Sintering (DMLS), Selective Deposition Lamination (SDL), Binding Jetting/Projet 3D Printing, Electron Beam Melting (EBM) and Laminated Object Manufacturing (LOM). Now AM has added some more 3D printing technologies which have massive benefits as compared to other traditional manufacturing technologies.^{5,6}

AM technologies can easily incorporate a design change in lesser time with the help of different software. It provides better quality products with a better reputation whereby giving higher customer

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<https://doi.org/10.1016/j.cegh.2019.08.002>

Received 2 April 2019; Received in revised form 6 June 2019; Accepted 3 August 2019

Available online 03 August 2019

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satisfaction. Its applications are in various fields like medical, dentistry, engineering, automobile, aerospace, architecture, food and agriculture.^{7–9}

This technology helps brings direct manufacturing of the product from the research & development phase as well as in the education environment. It creates possibilities for new development and direction in business, designer, manufacturer and researcher. It has excellent capabilities for highly geometric complex shapes and features which create unlimited possibilities in a production system.^{10–14}

By properly implementation of this technology in medical, it reduces the number of production steps of manufacturing of medical parts, material waste during production, inventory, eliminates the amount of tooling required and manufacture the complete part in less time and cost.^{14–16}

This paper studied about additive manufacturing and different processes of 3D printing technologies in detail. The ongoing research on additive manufacturing in a different field from the Scopus database is studied and analysed. Twelve important applications areas of additive manufacturing are identified and discussed in tabular format with proper references. Finally identified sixteen major materials used by additive manufacturing in the medical field.

2. Research questions

This article addresses the following research questions:

RQ1: To identify research papers from Scopus on the development of additive manufacturing in different fields and its printing of different types of materials for the medical field, after that analyse the contemporary research status.

RQ2: To study different processes of 3D printing and analyse advantages and limitations of AM

RQ3: To identified the development of AM in various fields and identified its primary applications with references.

RQ4: To identify materials as being through additive manufacturing for medical application and describe briefly the significant ones

RQ5: To identify the future development of additive manufacturing in different fields

3. Research status

3.1. Research status on additive manufacturing and its applications in different field

Research publications on additive manufacturing are rapidly

increasing; taking data from Scopus by searching keyword as “additive manufacturing” we find entire 16043 research articles until March 2019. In 1970 the first research article on additive manufacturing was published. Then the 2nd article was published in 1980; there was a gap of ten years. In the year 1982, 1983, 1986, 1990, 1993, 1995 and 1996, one article published in each year. It improved to three articles per year during 1997, 1998 and 2000. The year 2001 and 2002 have five publications per year. In 2003 (11), 2004 (14), 2005 (28), 2006 (32), 2007 (33) articles were published in respective years. Then additive manufacturing publications speeded from 2008 rapidly, and now much work is done in this new growing technology. In 2008 (45), 2009 (69), 2010 (189), 2011 (227), 2012 (363), 2013 (547), 2014 (1093), 2015 (1517), 2016 (2466), 2017 (3471), 2018 (4589) and till March 2019, 1321 articles are published in this year.

Different journals and sources published research articles on additive manufacturing, out of these top five journals and sources are Additive Manufacturing (500), Rapid Prototyping Journal (349), International Journal of Advanced Manufacturing Technology (347), Proceedings of SPIE The International Society For Optical Engineering (295) and Procedia CIRP (288). Other journals and sources also publish articles on additive manufacturing.

In areawise contribution on additive manufacturing, maximum contribution of 37% provided by Engineering field, Materials Science (22%), Physics and Astronomy (10%), Computer Science (10%), Mathematics (4%), Chemical Engineering (3%), Chemistry (3%) and other fields having 11% contribution, these includes Biochemistry, Genetics and Molecular Biology, Energy, Business, Management and Accounting, Medicine, Decision Sciences, Environmental Science, Social Sciences, Earth and Planetary Sciences, Multidisciplinary, Pharmacology, Toxicology and Pharmaceutics, Dentistry, Agricultural and Biological Sciences, Health Professions, Economics, Econometrics and Finance, Arts and Humanities, Immunology and Microbiology, Neuroscience, Psychology, Nursing and Veterinary.

From Scopus data, we have analysed that additive manufacturing applications are rapidly growing. It the next few years it will become more beneficial in different fields. AM also has a significant contribution in different fields, and much research is taken out by using this technology, as shown in Table 1.

By obtaining this data from Scopus, we analysed that additive manufacturing is making an excellent contribution to the field of manufacturing and design. This technology is accessible due to its manufacturing capability of any customised product and also easily creation for innovative designing of the part. There is very less work taken out by additive manufacturing in agriculture. In future AM application will explore in various other fields.

Table 1
Research status of additive manufacturing applications in different fields.

S No	Field	Searching keywords	First article published in the year	No of publications in the last year (2018)	Total no of publications
1	Medical	“additive manufacturing” “medical.”	2004	250	989
2	Dentistry	“additive manufacturing” “dentistry”	2009	27	88
3	Design	“additive manufacturing” “design”	1993	1599	5918
4	Manufacturing	“additive manufacturing” “manufacturing”	1970	4589	16043
5	Engineering	“additive manufacturing” “engineering.”	1995	688	2617
6	Research and development	“additive manufacturing” “research and development”	1998	24	101
7	Reverse engineering	“additive manufacturing” “reverse engineering”	2008	25	106
8	Aerospace	“additive manufacturing” “aerospace”	2000	230	881
9	Automobile	“additive manufacturing” “automobile”	2003	46	190
10	Architecture	“additive manufacturing” “architecture”	2008	154	646
11	Food	“additive manufacturing” “food”	1996	44	137
12	Agriculture	“additive manufacturing” “agriculture”	2016	1	6

3.2. Research status on materials used by additive manufacturing for the medical field

Research is undertaken on materials used in additive manufacturing for use in the medical field. By searching keyword as “additive manufacturing” materials” medical”, a total of 571 research articles are identified from Scopus. The first article was published in 2004; this year, two articles were published. Third article was published in 2006, 2007 (2), 2008 (2), 2009 (8), 2010 (9), 2011 (10), 2012 (10), 2013 (25), 2014 (51), 2015 (63), 2016 (86), 2017 (130), 2018 (131) and in 2019, up to March, 42 articles are published so far.

Different journals and sources publish research articles on materials used by additive manufacturing for the medical field, out of them, the top five journals and sources are Rapid Prototyping Journal (13), Additive Manufacturing (10), Procedia CIRP (10), International Journal of Advanced Manufacturing Technology (8) and seven articles were published by Journal of the Mechanical Behavior of Biomedical Materials. Other journals and sources also have a contribution to this specific field.

In areawise contribution on manufacturing of different materials to medical field using additive manufacturing, again Engineering field have maximum contribution of 33%, Materials Science (23%), Physics and Astronomy (8%), Computer Science (8%), Medicine (6%), Biochemistry, Genetics and Molecular Biology (5%), Another field provides chemistry (4%) and 13% contribution, these include Chemical Engineering, Mathematics, Business, Management and Accounting, Energy, Decision Sciences, Pharmacology, Toxicology and Pharmaceuticals, Dentistry, Environmental Science, Health Professions, Social Sciences, Multidisciplinary, Agricultural and Biological Sciences, Immunology and Microbiology, Neuroscience, Earth and Planetary Sciences, Psychology and Veterinary field.

4. Different processes as used in 3D printing

There are varieties of processes used in 3D printing of parts.^{14,17,18} Table 2 discusses the significant ones.

All these processes of printing a 3D solid object, using additive manufacturing layer by layers generally involve the following steps:

- Creating a 3D CAD model, either through a designing software or from 3D scanning technologies
- Conversion of virtual CAD files in STL format
- Printing of the parts using appropriate AM technologies
- Safe removal of the printed part
- Customised Post-processing of the part as to improve the strength & other properties

Steps used to create 3D medical model using additive manufacturing are as under:

- Create a 3D CAD model of the individual patient using computed tomography (CT), MRI (magnetic resonance imaging), 3D scanner or any design software
- Convert Digital Imaging and Communications in Medicine (DICOM)/3D CAD generated from these scanning technologies into STL format
- Printing of patient-specific implants using AM technologies
- Post-processing of implants
- Testing of implants
- Final implementation of the implant in the patient body

4.1. Advantages of additive manufacturing

Additive manufacturing has different advantages in design and manufacturing. It helps designs and development of a product without any requirement of fixture or tooling with shorter setup time. By using this technology, the manufacturer can quickly change for a revised version of the product. In the current scenario, there is a requirement of customisation, which is easily possible at a lower cost. It enhances on-demand production and can print complete object in one time. Now research and training program become comfortable when offered at all level. As compared to the traditional manufacturing process, AM has lesser energy usage with reduced material wastage in production. The main advantage of this technology is flexibility, by which it has different flexibility in design and manufacturing of the product. It helps creates innovation and increase industrial efficiency.^{7,17}

4.2. Limitations of additive manufacturing

There are also some main limitations of additive manufacturing. As compared to this technology, the traditional manufacturing process is usually much faster for mass production. Product manufactured having limited size depends upon machine print bed size. Per piece production cost can be high because the base material is expensive and no economy of scale. Only skill human resources required to operate these machines. In these machines, there is a low option of the material changing and printed part having poor surface quality. As the product is manufactured in one time and if there is any break during printing, the part will be damaged. After manufacturing of the part, there is a requirement of post-processing that increases the cost of the product.⁹

5. Development of additive manufacturing in different fields

Additive manufacturing is moving from research and development

Table 2
Different processes of 3D printing.

S No	3D printing processes	Description
1	Vat Polymerization	<ul style="list-style-type: none"> • The part is manufactured in a vat of liquid resin photopolymers • The UV light is precisely directed through mirrors on the object to build a required shape
2	Powder Bed Fusion	<ul style="list-style-type: none"> • Uses an electron beam, laser or thermal print head to melt the ultra-fine layer of material in a 3D space
3	Material Extrusion	<ul style="list-style-type: none"> • It is the process, where the raw material is extruded through a heated nozzle that moves horizontally by adding melted material layer by layer, and the bed moves vertically
4	Directed Energy Deposition	<ul style="list-style-type: none"> • Electron laser or gun is used to melt wire, powder or filament feedstock • This process uses a wider variety of materials like metals, ceramics and polymers
5	Sheet Lamination	<ul style="list-style-type: none"> • 3D physical models are manufactured layer by layer processes of the defined sheet of materials • A laser is used to cut material which is in shape of a sheet as per the required cross-section Sheets are joined with the help of adhesives and product is manufactured by repeating the steps
6	Material Jetting	<ul style="list-style-type: none"> • Like 2D inkjet printer, this technology also uses material jetting print head that moves back and forth • To create a 3D physical object, it typically moves in x, y and z-axis • In this process, ultraviolet light is used to harden the layers
7	Binder Jetting	<ul style="list-style-type: none"> • Powder and binder is used as a raw material to build a 3D solid object • The powder is spread layer by layer and binder is used to bind the powder with the help of a print head

Table 3
Development in different fields by the application of additive manufacturing.

S No	Field	Developments	References
1	Medical	<ul style="list-style-type: none"> ● In the medical field, AM is the most emerging technology as applied to achieve complex surgical problem and various other designs and manufacturing of medical implant, tools and devices. ● Its applications are for biocompatible materials with high strength and flexibility ● Provides new opportunities to save the life of the patient by producing exact fit medical implants ● Its applications are for orthopaedic implant devices, pre-surgical model, and some special tools and instrumentation ● Produce exact fit implant from patient data captured by different scanning; as a result, it improves patient outcomes ● Also applied in medical for new tooling design and development, medical education and training 	Melchels et al., 2010 ¹⁹ ; Salmi et al., 2013 ²⁰ ; Tuomi et al., 2014 ²¹ ; Arafat et al., 2014 ²² ; Javaid and Haleem, 2017 ²³ ; Banga et al., 2018 ²⁴
2	Dentistry	<ul style="list-style-type: none"> ● Additive manufacturing is used for customising the design and undertake the production of dental implants, tool, instruments and other dental devices ● Easily print customised dental crowns, orthodontic braces, aligners, removal prosthetics, surgical templates, bridges and various other models in lesser time and cost ● Dental implants are produced accurately as per the patient data, captured by various scanning devices like dental 3D scanner ● Used for easy replacement of teeth, braces, crown, veneers, dentures, and aligner during complicated cases ● In upcoming years AM will bring significant innovation and new tool and devices in dentistry 	Chan et al., 2004 ²⁵ ; Azari and Nikzad, 2009 ²⁶ ; Chen et al., 2014 ²⁷ ; Bae et al., 2017 ²⁸ ; Javaid et al., 2018 ²⁹
3	Design	<ul style="list-style-type: none"> ● AM creates flexibility in the design and development of various products like aeroelastic models and ergonomically new designing of any product ● Create accurate design as per required shape with high accuracy and reliability in lesser time ● It is the faster technique of designing any new product as compared to the existing method ● Creates better geometric freedom and physical test model whether it may be feasible or not before starting full production system ● Reduced tooling cost in the product design process ● It simplified the design process, which makes almost any shape of product using any material 	Vaughan and Crawford, 2013 ³⁰ ; Adam and Zimmer, 2015 ³¹ ; Tang and Zhao, 2016 ³² ; Yao et al., 2017 ³³
4	Manufacturing	<ul style="list-style-type: none"> ● AM used in various fields like medical, defence, industries, automotive for the manufacturing of various customisation products and up gradation of tools as per requirement ● Creates excellent flexibility in manufacturing as compared to the conventional method ● Capability to create a unique product quickly with great success ● In the current scenario, it also plays an active role in the concept generation process by manufacturing prototypes 	Spierings et al., 2013 ³⁴ ; Borille et al., 2017 ³⁵ ; Costa et al., 2017 ¹⁷ ; Ballardini et al., 2018 ³⁶ ; Haleem et al., 2019 ³⁷
5	Engineering	<ul style="list-style-type: none"> ● In the engineering field, AM is used to manufacture prototype as well as various engineering parts ● It has vast applications in cast mould, sub-scale turbine blade mould and various other useful engineering components ● Product printed by AM technologies is useful for modern engineer's training ● Useful for engineering designing and manufacturing to create innovation in the product 	Campbell et al., 2012 ³⁸ ; Rylands et al., 2016 ³⁹ ; McMillan et al., 2017 ⁴⁰ ; Muir and Haddud, 2018 ⁴¹
6	Research and development (R&D)	<ul style="list-style-type: none"> ● AM is for R&D of different industrial and other products which required modification than that of existing products ● Easily converts first design idea into a finished prototype with no detours along the way ● Manufacture prototype and can further check performance before actual implication whether the product performs satisfactorily or not ● Quickly made changes in the product development phase as compared with conventionally made products with minimal extra cost 	Soe et al., 2012 ⁴² ; Ghadge et al., 2018 ⁴³ ; Bastola et al., 2018 ⁴⁴
7	Reverse engineering	<ul style="list-style-type: none"> ● There are two different way to develop a new product, first is the new design and another is taken from a sample as a reference called reverse engineering ● AM reduces the number of design iterations and increases the efficiency and reliability of the product by reverse engineering concept ● This technology is possible to reach optimal design, reduce the time and minimise the cost of products on the market while reverse engineering ● In the medical field, it also has a high capacity to produce missing bone/part of the body 	MinetolaandIuliano, 2014 ⁴⁵ ; Tanwilaisiri et al., 2018 ⁴⁶ ; Haleem and Javaid, 2018 ⁴⁷

(continued on next page)

Table 3 (continued)

S No	Field	Developments	References
8	Aerospace	<ul style="list-style-type: none"> AM technologies produce complex aerospace parts with high strength and low weight This direct manufacturing technology is now readily available for design and manufacturing of cosmetic aircraft interior components, tooling for composite, rocket engine components, combustor liners and fuel tank components Various companies push forward this technology for innovative design and world-class parts in aerospace industries Used for the designing and manufacturing of jet turbines and rocket engines 	JarallahandKanjirakkad, 2016 ⁴⁸ ; Strong et al., 2017 ⁴⁹
9	Automobile	<ul style="list-style-type: none"> In the automobile industry, AM produce lightweight components to become more active and increasing the efficiency of vehicles It can build customised automobile parts with high complex geometries in the lesser cost which is not easily possible by traditional manufacturing technologies It opens new opportunities for the mass customisation of product in this sector Excellent ability to reproduce part with innovative design with better feature It opens a new door for lighter, cleaner, and safer products with lower cost and shorter lead times 	Marchesi et al., 2015 ⁵⁰ ; Cooper et al., 2015 ⁵¹ ; Dwivedi et al., 2017 ⁵²
10	Architecture	<ul style="list-style-type: none"> AM is capable of translating the virtual3D model into a 3D printed physical model which is helpful in the construction of buildings Used for developing building services in which building models that show textures, colours and shapes This technology developed and now it is capable of constructing actual concrete houses at low cost In the next few years, AM will be a part of the architecture ecosystem and become beneficial for construction of buildings 	Gerard et al., 2001 ⁵³ ; Gibson et al., 2002 ⁵⁴ ; Giannatsis et al., 2002 ⁵⁵ ; Buswell et al., 2007 ⁵⁶
11	Food	<ul style="list-style-type: none"> AM is also applicable to the design and production of customised food that creates significant innovations in the food industry It is a practical approach for various food items like customised pizza, burger, cake, chocolate etc. as per the requirement of the customer It has multiple advantages in the food sector such as customised food designs, personalised nutrition It simplified the supply chain and its related applications in military and space AM technologies can easily prints meals on the particular demand of the customer as required quality and quantity 	Koyratty et al., 2014 ⁵⁷ ; Godoi et al., 2016 ⁵⁸ ; Pallottino et al., 2016 ⁵⁹ ; Liu et al., 2017 ⁶⁰
12	Agriculture	<ul style="list-style-type: none"> Capability to cook or print customised food in our everyday life In the agricultural field, this new rising technology can produce physical models of agricultural equipment by which a functional prototype is manufactured easily The prototype manufactured by this technology is tested for obtaining the design of various agricultural requirements before the product is made in the factory It creates innovation in the agriculture sector by which the farmer will be able to purchase agricultural equipment according to their choice Customised types of equipment produced with the help of AM technology are according to land and hilly area requirement Various agricultural equipment like a plough, seed drill, land leveller, hand sickle, straw reaper etc. are efficiently designed and developed by this technology 	Pearce, 2015 ⁶¹ ; Vázquez-Arellano et al., 2016 ⁶² ; Javaid and Haleem, 2019 ⁹

to production line. It provides high flexibility in design and manufacturing that help to create capability whatever we want. Table 3 describes the astounding capabilities of AM.

The primary applications of additive manufacturing technologies are applied for research and development, making models for prototype tooling, making functional parts and tooling components, the pattern for metal castings, presentation models and visual aids. Additive manufacturing has excellent potential to create useful part and gives an actual work performance as per requirement. It will become a successful commercial technology, thereby contributing development in various application fields.

6. Different types of materials used in additive manufacturing for medical applications

Technologies used in additive manufacturing provide flexibility for

the production of any shape, size and texture. Different technologies use different types of materials. AM creates exact replicas of patient-specific applications to perform complicated operations. It is used in cardiology for the manufacturing of different heart valves, stents and also helpful presurgical planning.⁶³ As compared to another traditional process, this technology can produce surgical instruments at a lower cost. It produces customised prosthetic limbs which easily suits and fits the wearer.⁶⁴ Everyday 3D printers are developing to print different material like plastics, concrete, composite, metals, paper, organic materials and food. A wide variety of material is used to create 3D objects for the medical field. Different types of materials being used in AM technologies are discussed in Table 4.

Additive manufacturing helps improve human life, by replacing a human organ, manufacturing prosthetic limbs, surgical tools and speed up surgical procedures. In the medical field, there are requirements for effective communication and materials.¹⁰² Additive manufacturing is

Table 4
Materials used in additive manufacturing by 3D printing applications in the medical field.

SNo	Materials	Description	References
1	Plastic	<ul style="list-style-type: none"> ● Plastic is the most common raw materials for 3D printing ● Without plastic material, healthcare is not possible due to lesser painful for health ● FDM printers used this material in the form of filaments which is quickly melted and manufactured medical parts layer by layer ● Used to manufacture heart valve, intravenous blood bags, disposable syringes, eyeglass frame and lenses ● Provide greater comfort, flexibility and mobility due to its transparency, durability and lightweight ● Used to manufacture thin tube which helps to unblock blood vessels 	O'Neill et al., 2008 ⁶⁵ ; Singh, 2014 ⁶⁶
2	Silicone	<ul style="list-style-type: none"> ● Silicone is used to manufacture different medical implants like tracheal stents ● Used for the manufacturing of single-use and reusable components, diagnostic instruments and other surgical tools ● It offers versatility and biocompatibility applied to manufacture medical wires and cable components 	Bajpai and Bajpai, 2010 ⁶⁷ ; Haleem and Javaid, 2018 ⁶⁸
3	Acrylonitrile butadiene styrene (ABS)	<ul style="list-style-type: none"> ● It is a popular material used by FDM in the form of the filament ● This material having high rigidity, dimensional stability and surface brightness ● Used for the manufacturing of insulin pens, inhalers and blood access devices by AM technologies 	Chohan et al., 2018 ⁶⁹ ; Haleem et al., 2018 ⁷⁰
4	Polylactic acid (PLA)	<ul style="list-style-type: none"> ● Also used in jewellery and vases due to its strength ● PLA is a stronger material used to manufacture a broader range of product in the medical field ● Due to its high biocompatibility, it is used for tissue engineering application like bone ● Used as wound management of dental extraction, surgical sutures and preventing postoperative adhesions ● PLA manufacture stents which are applicable for better treatment of war surgeries ● Preferably used for the manufacturing of biodegradable fixation pins, screws, suture anchors and plates 	Drummer et al., 2012 ⁷¹ ; Hamad et al., 2015 ⁷² ; Grasso et al., 2018 ⁷³
5	Metal	<ul style="list-style-type: none"> ● Metal printing is the most popular material in the 3D printing industry ● Direct metal laser sintering 3D printing is used to print metal parts for medical ● In the medical field, metals implants are used for more than 100 years such as a metal plate for fixation of a fractured bone ● Now additive manufacturing technologies are available to print patient-specific metal implants ● Used for artificial joints, stents, plate, screw and valves where we require high wear resistance ● It is biocompatible used for long term implantable devices and has no harmful for human tissues 	Wang et al., 2018 ⁷⁴ ; Paul et al., 2018 ⁷⁵ ; Jin et al., 2018 ⁷⁶
6	Polyvinyl Alcohol Plastic (PVA)	<ul style="list-style-type: none"> ● Used for the manufacturing of temporary items and also works as support material ● This material is also printed by 3D printing having the ability to reduce blood loss ● Pellets, sheets, sponges, foams, coatings, meshes, and microspheres are efficiently manufactured by this material using this technology ● 3D printing technology is also applicable to print smart material which can change the shape of the printed part concerning the time 	Duran et al., 2015 ⁷⁷ ; Javaid and Haleem, 2018 ⁷⁸
7	Tissue and cell	<ul style="list-style-type: none"> ● 3D printing technologies are also applicable to print tissue ● It improves whole organ/damaged tissue and helps to create desired cell type ● 3D printing made entire organs for transplantation and developed dozen of human tissue repair products ● This technology easily maintain, restore, improve damaged tissue and whole organs ● AM is the best technique to print living cell easily 	Khalil et al., 2005 ⁷⁹ ; Vasireddi and Basu, 2015 ⁸⁰ ; Zheng et al., 2017 ⁸¹
8	Powder	<ul style="list-style-type: none"> ● Powder materials are used to construct products inside the printer ● In this process, the powder is sintered/bind as per desired thickness ● Powder materials 3D printed part is used to presurgical planning for complex surgery ● Improve communication between patient and surgeon ● The best technique for training and education of the medical student 	Lanzetta and Sachs, 2003 ⁸² ; Dressler et al., 2010 ⁸³
9	Alumide	<ul style="list-style-type: none"> ● This material is mixing of gray aluminium, polyamide, alumide powder and manufacture stronger 3D models ● This material is easy to transport and make the desired shapes ● Used for manufacturing of customised 3D parts for medical like hearing aids, orthosis and prosthetic hands 	Tiwari et al., 2015 ⁸⁴ ; Nsengimana et al., 2019 ⁸⁵
10	Carbon Fiber	<ul style="list-style-type: none"> ● Carbon fibre is used in 3D printers for top coating of plastic material used for medical applications ● Used to manufacture patient's lost limb ● This technology also manufacturedifferent medical tools in lesser time and cost 	Yang et al., 2017 ⁸⁶ ; Haleem et al., 2019 ⁸⁷
11	Nitinol	<ul style="list-style-type: none"> ● Additive manufacturing technology is also helpful in the fourth industrial revolution ● Commonly used for the manufacturing of medical implants due to its superelasticity ● This material is the mixture of titanium and nickel ● It can bend easily without any breaking as per requirement ● This technology is used to create personalisation in the medical field 	Bibb et al., 2010 ⁸⁸ ; Haleem et al., 2018 ⁸⁹
12	Polyurethane foam	<ul style="list-style-type: none"> ● It is used for manufacturing of scaffolding implants, medical devices, surgical drapes, catheter tubing etc ● Applicable for different variety of injection moulded devices and short term implants 	Cook et al., 2010 ⁹⁰ ; Horn et al., 2014 ⁹¹

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Table 4 (continued)

SNo	Materials	Description	References
13	Graphene	<ul style="list-style-type: none"> This material has high abrasion, strength and biocompatibility It is a flexible material having popular due to its conductivity and strength Used during cancer treatment applications Graphene material 3D printed implants reduce the infection in the patient body 	Pei et al., 2015 ⁹² ; Sayed et al., 2016 ⁹³
14	Titanium	<ul style="list-style-type: none"> Applicable to coat stents and different medical devices to make surgery safe This material is used to manufacture of hip implants, bone crew and heart valves. It is biocompatible and non-allergenic Titanium is lightweight, stronger and rigid as compared to other materials 	Liu et al., 2018 ⁹⁴ ; Skawiński and Goetzendorf-Grabowski, 2019 ⁹⁵ ; Haleem and Javaid, 2019 ⁹⁶
15	Polyethylene	<ul style="list-style-type: none"> Also applicable to the manufacturing of dentistry part by the input of smart material Polyethylene is used to manufacture implants for knee and hip replacement which provides cushioning and movement It preferably used in medicine due to its porous synthetic polymer which is biologically inert and not harmful for the body 	Lifton et al., 2014 ⁹⁷ ; Begines et al., 2016 ⁹⁸ ; Javaid and Haleem, 2019 ⁹⁹
16	Polyether ether ketone (PEEK)	<ul style="list-style-type: none"> This material provides development in the health care industry PEEK material having excellent biocompatibility, less weight, good mechanical properties, high tensile strength, low moisture absorption and high flexibility It is colourless, and the model manufactured is suitable for various medical applications Used for the manufacturing of Orthopaedic implants, Medical tubing, Spinal implants, Bone screws and pins, Heart valve and stents, Dental implants FDM 3D printing technology is used to print this material 	Gallagher et al., 2018 ¹⁰⁰ ; Haleem and Javaid, 2019 ¹⁰¹

one of the important technology helpful medical and in upcoming industrial revolution.¹⁰³ This technology is used for bioprinting with appropriate medical material. It can manufacture a living cell, artificial living tissue for a medical laboratory.¹⁰⁴ This can easily create a surgical mesh which supports tissues and organ during surgery.

7. Discussion

Additive manufacturing employs lots of emerging technologies, and many of them are reported through research articles. In the medical field, it has a significant contribution because data of the patient vary from one another. This creates exact fit medical implants, tools and instrumentation as per requirement of the patient. It prints different materials which are successful in the medical field. Different technologies provide different flexibilities, and with different materials, it produces the exact fit medical part for the patient. It provides the best solution to save the life of the patient. It is applicable for the design and manufacturing of a high strength medical parts, tools and devices as per the requirement. It fabricates lightweight parts/components with highly sophisticated and innovative geometries. Its applications are for the design and development of customised design and production of dental implants, crown, braces, tool, instruments and various other dental devices accurately produced as per the requirement of the patient. The design and development of any medical devices are also done for medical education and training. AM also contributes to research and development of various industrial and other products. This technology is applicable to reverse engineering by producing the missing part. In upcoming years, AM will bring innovation in various other fields.

8. Future development

In the future, AM will help to create innovation for socio-technical change by printing multiple categories of objects including medical parts, car and aircraft parts, toys, fashion accessories, customised mobile phone cover, jewellery, smart medical implants. This technology will come up with some significant innovations in future such as at the same time, the printing of mix and smart materials. It plays an active role in the reduction of cost and development time in all fields. By using AM, there is an incremental innovation in the medical industry. It enables to visualise doctor and help to improve better communication. AM technologies are now available to provide a full-colour product which is much helpful for the demonstration. By using a wide variety of material, it produces superior quality and speed with higher precision.

In the next decade, AM can help to reduce shipping costs, reduce lead time and shorten supply chains. The future of this technology looks bright and more prominent in the design and manufacturing landscape. By the concept of 4D printing, which is the extension of 3D printing, it prints smart object which is self-assemble and changes the shape of the printed object concerning time and variation in temperature.

9. Conclusion

Additive manufacturing plays a vital role in product design and development by reducing product development cycle time, costs with improved quality of the final product. The design and development of the product are done efficiently as compared to another traditional machining process. Numbers of papers on additive manufacturing in different fields and its printing of different materials for the medical field are studied and analysed. It is observed that higher flexibility for the printing of customised and complex medical with intricate shape and size, which was not previously quickly possible and feasible. AM produce medical parts using different materials with different shape and size as per demand. It is an essential tool for digital manufacturing in the rapid product development process. For highly geometric, intricate shapes and irregular features, it has unlimited possibilities in the production system and reduces the number of production steps, inventory and material waste. In future, this technology will play a vital role in any product design, development and customisation of medical products/instruments to improve the efficiency.

Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cegh.2019.08.002>.

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