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Global perspective and African outlook on additive manufacturing research – an overview

Desmond Edem Primus Klenam[1,2,*], Olufemi Sylvester Bamisaye[2,3], Iyanu Emmanuel Williams[2], Josias Willem van der Merwe[2], and Michael Oluwatosin Bodunrin[2]

[1] Academic Development Unit, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, South Africa
[2] School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, South Africa
[3] Mechanical Engineering Department, Air Force Institute of Technology, Kaduna, Nigeria

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Abstract. Additive manufacturing (AM) technologies and advances made globally in medicine, construction, aerospace, and energy sectors are discussed. The paper further explores the current state of AM innovation and development landscape in Africa as a late comer to this area of smart manufacturing. Peer-reviewed and published literature were retrieved from Scopus database from 2005 to 2021 and analysed. In Africa, out of 500 published articles, South Africa has the highest research throughput, whereas about two-thirds of the continent is not actively participating in this burgeoning field. The main AM techniques most widely used are selective laser melting, fused deposition modelling, and direct energy deposition. Globally, there is an interplay of computational (machine learning and mechanistic models) and experimental approaches to understanding the physical metallurgy of AM techniques and processes. Though this trend is consistent with global practices, Africa lags the world in AM technologies, a niche that could leapfrog the manufacturing sector. Thus, Africa need to foster collaborative partnership within and globally to become an active global player in this industry.

Keywords: Additive manufacturing / Africa / 3D printing / Research throughput

1 Introduction

Additive manufacturing (AM) or three-dimensional (3D) printing is a branch of smart manufacturing [1,2]. It creates prototypes or functional components using a digital file which are built using an incremental (layer-by-layer) manufacturing process. Thus, it is the deposition of layers of thin material upon each other to produce a final three-dimensional component [3,4]. This deviates from subtractive manufacturing, where components are prefabricated and then machined to the desired and designed geometry. Most AM uses powder-based or wire feedstocks to produce the final component based on a digitally defined path [5]. Since the 1980 s, AM technology has been revolutionary and backed by active research endeavours globally. This shows how the science and physical metallurgy of the process are evolving as shown in Table 1. In recent times, AM is a competitor for conventional subtractive manufacturing [6] due to benefits such as low production cost, high production volume and ability to product components of varying degrees of complexities as illustrated in Figure 1 [2].

Globally, the drivers and enablers of technological advancements are the multi-disciplinary and convergence of biotechnology, information technology and materials science and engineering. This has been demonstrated in the design of state-of-the-art diagnostic test kits, swift and quick manufacturing of protective equipment and the drive for a vaccine within weeks in the wake of the corona virus pandemic. The role of AM techniques has been critical to that endeavour. Intricate and near net shapes of components were designed with minimal wastage of material and deployed at a much faster rate (Fig. 1) [7]. This was done at a low cost and environmentally friendly manner. Lightweight components were also produced with high structural integrity. Thus, the merits of AM processes outweigh the demerits and more disruptive to the conventional manufacturing methods (Fig. 1). These include easy manufacturing, mass customization, reduced labour, industrial efficiency, on-demand manufacturing, decentralized manufacturing, component manufacturing, and quality improvement [2,10]. This makes AM versatile for mass production of structural and functional components [9]. These applications are mostly in industries

* e-mail: desprimus@gmail.com

Table 1. Timelines and major contribution to additive manufacturing since its inception.

Year	Major contribution to additive manufacturing
1981	First rapid prototyping
1984	First stereolithography (SLA) prototype
1991	First fused deposition modelling (FDM) machine operationalized
1992	First SLA 3D printer operationalized
1997	Operationalized first laser additive manufacturing system
2000	First 3D Inkjet printer
2001	First desktop 3D printer
2002	First miniature kidney was printed
2005	Replicating rapid project for low-cost 3D printers
2008	First 3D prosthetic leg printed
2009	First 3D printed blood vessel
2010	First Prusa Mendel 3D printer
2011	First 3D printed edible food
2012	First 3D printed jaw
2013	First 3D printed rocket parts
2014	First zero-gravity 3D printer
2015	Ultrafast clip 3D printer
2016	3D printed bone
2017	3D printed farms
2018	3D printed glass
2019	First 3D printed human heart
2020–	Optimization of mechanical properties and heat treatment behaviour

such as medicine [10–44], construction [45–53] and aerospace product design [2,3,6,54–62]. Despite the advantages and benefits of additive manufacturing, there are several challenges to adopting this technology. These includes but not limited to size restrictions, production time, cost, and regulations [3].

There have been reviews on AM techniques, materials, processes, and industrial applications in aerospace, healthcare, energy, building and construction [10–40]. A thematic review on the modelling of the various AM processes with the key performance indicator has also been carried out [63]. Most of these reviews and research outputs are Americentric and Eurocentric since developed economies have industries and research centres with state-of-the-art facilities enabling innovation in AM [2,3,6,54–62]. Countries with some of the highest patents in AM are in the global north [64,65].

Africa lagged the global North in most of the matured and emerging technologies. Africa is a passive participant in research and development across various frontier fields of materials science and engineering. While there is continental interest in AM/3D printing, the state and current areas of research and development need to be ascertained. This is because the state of AM research throughput in Africa is vaguely known. Thus, the aim of this study is to access the state of additive manufacturing globally while zeroing in on Africa. The novelty of this review is the assessment of current state of research on the continent using published resources from various databases while focusing on milestones, prospects, and opportunities which can be vaulted into the industrialization of Africa. This paper reviewed additive manufacturing techniques, materials, and trends globally and in Africa. The applications of additive manufacturing and how they cut across several disciplines, such as medicine, aerospace, manufacturing, building and construction, and quality control assessment, are discussed. The research output of additive manufacturing; awareness; education; and training in Africa and globally was discussed. This review concluded with the perspectives for future research directions in additive manufacturing.

2 Methodology and study approach

Published literature was assessed focussing on key concentration of additive manufacturing research and development in Africa. Journal articles, conferences and monographs indexed in Scopus database were extracted for the study. Keywords such as "Additive Manufacturing" and "3D Printing" from January 2015 to September 2021 was used. The keywords were examined in the title, abstracts and then integrated to prevent double counting. Individual publications were examined focusing on the affiliations of the authors and collaborating institutions, research focus, type of paper, respective fields that the research was conducted, year of publication and country. Documents with no affiliations in Africa were excluded. Though the review focused on research in Africa, global outlook on the application and current stage of AM research was summarized for contextual understanding.

3 Additive manufacturing techniques, materials, and trends

The ASTM F2792-12a and ISO 52900 classify 3D printing under seven main types [66]. These typical methods are binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization. These methods are further discussed with suitable materials and the benefits, resolution and the principal areas of applications are given in Table 2.

Binder jetting involves joining by selective deposition of liquid bonding agent on thin layers of powdered material [63,67,68]. Materials used for binder jetting are, metals, ceramics, composites, and polymers. Examples of applications are surgical implants, moulds, and lightweight structures [36–40]. An individual process is the 3D printing direct energy deposition (DED) uses laser or electron beam which is directly focused on a small region of the substrate while melting the feedstock material (powder or wire) simultaneously. Examples are laser engineered net shaping (LENS) [94], directed light fabrication (DLF) and direct metal deposition (DMD). This technique has been used for manufacturing high-performance superalloys [63]. The melted material is then deposited and fused into the melted substrate and solidified after movement of the laser beam [67].

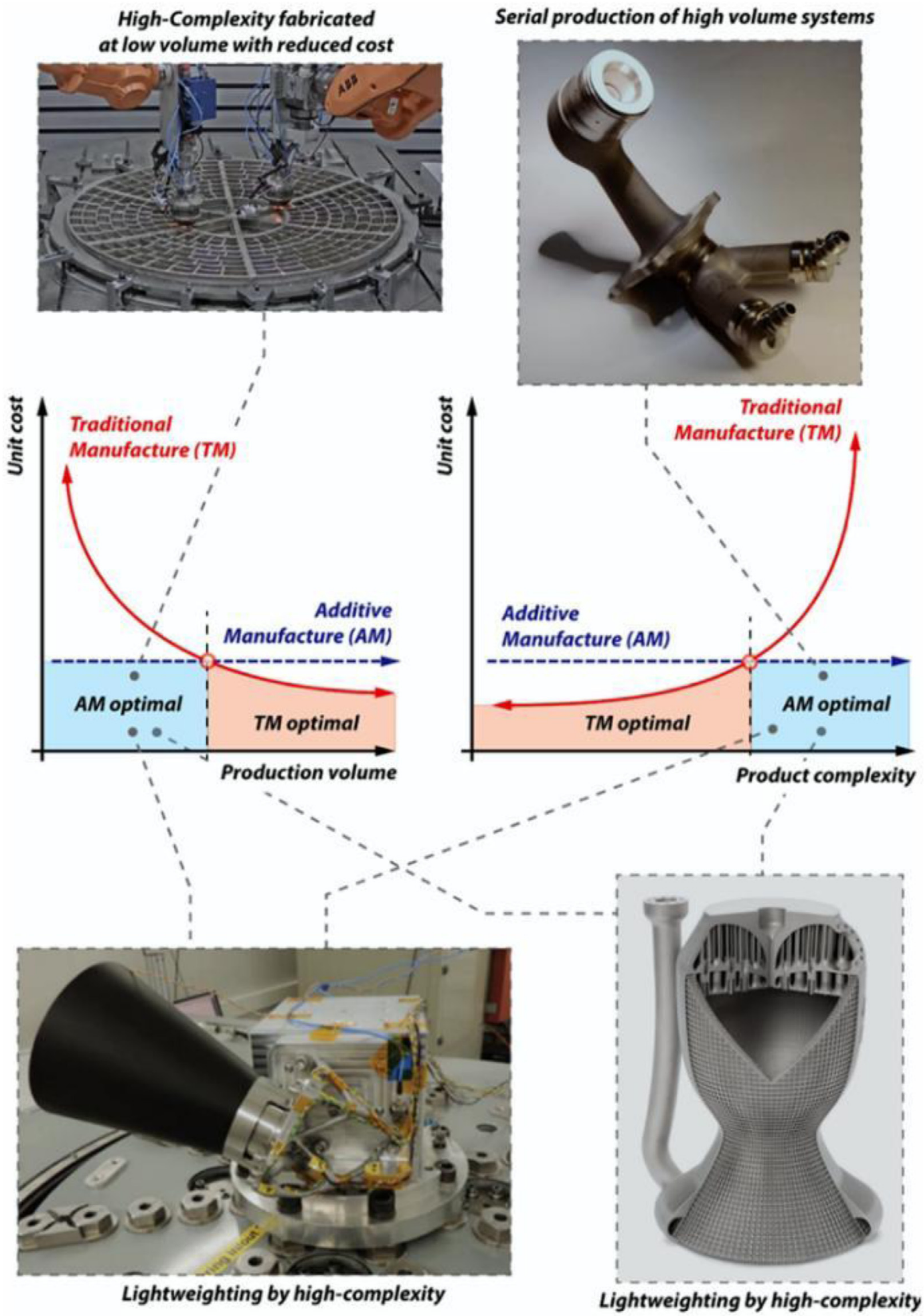

Fig. 1. Demonstration of AM satisfying multiple criteria such as high structural complexity, low-cost and high production volume [2].

Material Extrusion (ME) is the process of drawing a metal from a nozzle after the application of heat and the deposition is carried out layer by layer. It is an inexpensive and widespread process. Typical example of material extrusion is fusion deposition modelling (FDM), robocasting and multiphase jet solidification (MJS). This FDM method involves a continuous filament of a thermoplastic, polymer, and composites used to 3D print layers by layers of materials [63]. 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 [11–13]. Applications are in the medical and biomedical industries as biosensors and prosthetics, as well as in automotive and aerospace industries [13–16].

Table 2. Typical benefits of classes of AM methods and various applications with typical resolutions.

AM Method	Classes of materials	Merits	Demerits	Applications	Resolution (μm)	References
PBF (SLM)	Metals	Good mechanical properties Fabrication of complex geometry No need for extra support Highly dense	Not cost effective Development of residual stresses Product with rough surfaces Tedious and time consuming	Biomedical Shipbuilding Automotive Aerospace	80–250	[81–90]
PBF (EDM)	Metals	Great mechanical properties Great for complex geometry No additional support needed	Astronomical in terms of cost Poor surface quality Time consuming process	Automotive Biomedical Aerospace Marine	50–100	[89,92]
PBF (SLS)	Polymer Metals	Good mechanical properties Fabrication of complex geometry No additional support needed Great for powder processing	Energy efficiency is low Astronomical in terms of cost Low density	Biomedical Marine Automotive Aerospace	76–100	[89–91]
DED	Metals Ceramics Polymers	Good mechanical properties Fast cooling and solidification Cheap processing route Efficient processing and repair time	Low resolution Low surface quality of product Not great for complex parts	Aerospace Biomedical General repairs	250	[90]
ME (FDM)	Polymers	Low cost of fabrication High speed of fabrication Simple to operate	Poor mechanical properties Limited to polymers	Biomedical Toys	50−200	[71,72]
Sheet lamination (LOM)	Polymers Ceramics Metals Paper	Reduce manufacturing and tool time Low cost Variety of materials allowable Good for large structure production	Poor surface finish Poor dimensional accuracy Limitation for complex and intricate part manufacturing	Electronics Smart structures Paper fabrication Aerospace	Driven by laminate thickness	[77,89,90]
Vat (SL)	Polymers	Fine resolution Excellent quality of finished product	Applicable to limited materials Slow printing rate Expensive	Biomedical	10	[84]

Material jetting (MJ) is used to create objects like that of inkjet printing. The material is jetted onto the build platform and then allowed to solidify where the component is built layer by layer. This material is deposited from a nozzle and these layers are hardened using and ultraviolet light. Generally, waxes and polymers are suitable for this AM approach due to the issues around viscosity as the materials are deposited in drops. Due to the deposition being carried out in droplet, there is very low rate of wastage associated with the method. The MJ process also has high accuracy of deposition. Some of the industrial processes under MJ are multijet/polyjet modelling (MJM/PJM) and direct printing (DP).

Powder Bed Fusion (PBF) methods use either electron or laser beam to melt and then fuse materials mostly in the powdered form together [63,79,80]. This process is used for metals and polymers. Examples of PBF methods are direct metal laser sintering (DMLS), electron beam melting (EBM), selective heat sintering (SHS) and selective laser melting (SLM). In the case of EBM, parts are built by melting metal powder layer by layer with an electron beam in a high vacuum chamber [55,63,73–75]. In the case

Table 3. Developmental timelines of representative categories of laser metal AM technologies [95].

Laser based techniques	1980 s–2000 s	2000 s–2020 s
Laser directed energy deposition (LDED)	Laser cladding of coatings Laser categories: CO_2 laser, 10 kW (1986) Nd:YAG laser, 500 W (1995) Diode laser, 940 nm, 1.4 kW (1998) Laser and printing parameters: Typical beam size, 0.6 − 4 mm Energy intensity, ~10^4 Building rate, 0.1–4.1 cm^3/min	Laser additive manufacturing Laser categories: Diode laser, 10 kW (2015) Disk laser, 10 kW (2015) Fiber laser, 12 kW (2015) Nd:YAG laser, 4 kW (2016) Laser and printing parameters: Typical beam size, 3–6 mm Energy intensity, ~10^5 W/cm^2 Building rate, 11.5 cm^3/min
Laser powder bed fusion (LPBF)	Laser sintering Laser categories: CO_2 laser, 100 W (1993) Nd:YAG laser, 100 W (1997) Beam quality factor (CO_2 laser): 3-5 mm.mrad Typical beam size, 0.3–0.5 mm Energy intensity,10^4–10^5 W/cm^2 Building rate, ~0.2 cm^3/min	Laser melting Laser categories: Disk laser, 1 kW (2011) Fiber laser, 200 W (2012) Green laser, 515 nm, 1 kW (2020) Beam quality factor (Fiber laser): 0.3–4 mm.mrad Typical beam size, 70–200 μm Energy intensity, 10^6–10^7 W/cm^2 Building rate, ~1.3 cm^3/min

of DMLS, SLM and SLS, the energy source is from laser. The materials used for EBM, DMLS, SLM and SLS are steel, Cu alloys, Al alloys, and Ti alloy [75]. In the case of SHS, polymers are mainly processed using this approach. These AM techniques have been used in aerospace, automobile, marine, jewelleries, tooling equipment, moulds, lightweight components, and scaffolds for tissue engineering [8–11].

Sheet lamination processes include laminated object manufacturing (LOM), ultrasonic additive manufacturing (UAM) and plate diffusion brazing (PDB). The LOM is one of the first commercially available AM methods [63]. This is a layer-by-layer cutting and lamination of sheets or rolls of materials [76]. Successive layers are cut precisely using a mechanical cutter or laser and then bonded together [4,31]. This has been used in various industries such as paper manufacturing, foundry industries, electronics, and smart structures [31–34]. The UAM uses ribbons or sheets of metals bonded together using an ultrasonic welding.

Vat polymerization uses liquid photopolymer resin to form a model layer by layer. The model is then hardened by the application of ultraviolet light. Polymers and plastics are the main materials used for this technique of AM. Typical example is the Stereolithography (SL). This is one of the earliest methods of AM that uses ultra-violet or electron beam to initiate a chain reaction on a layer of resin or monomer solution [63,82,83]. It can be efficiently used for 3D printing of complex nanocomposites for biomedical applications [22,25–29].

There is a constant push for the use of AM processes mostly in the aerospace and biomedical industries. This could be due to the complex and intricate shapes associated with these industries. They are industries where cost can be traded for good mechanical properties and performance.

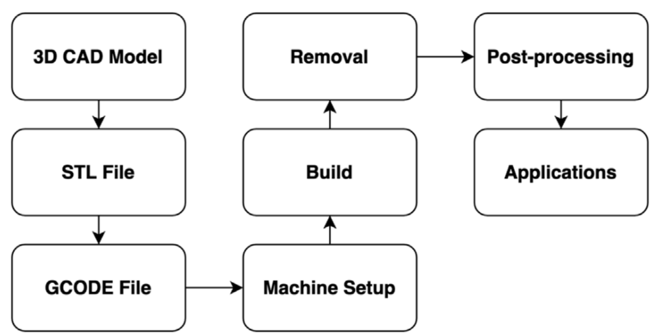

Fig. 2. Steps involved in AM/3D printing process.

Factors influencing the types of additive manufacturing are cost, type of material, build volume, post-processing requirements, surface finish, dimensional accuracy, and layer thickness [86].

The AM methods commonly used for metallic materials, which is laser-based is summarized in Table 3. These are being used in welding, turbine repairs, healthcare and coating [17–20]. The laser directed energy deposition (LDED) is used to build components by simultaneously delivering the material and the energy on the exact spot. Generally, the laser beam is used to melt the selectively deposited material on the surface. The laser powder bed fusion technique is unique for miniature to medium size components with internal and intricate geometries and shapes.

The simplistic and high-level processes involved in 3D printing are given in Figure 2 [67,96]. It starts with the 3D Model, which is used to generate a standard tessellation language (STL) file. This STL file is then converted to GCODE, a numerically controlled program for instructing

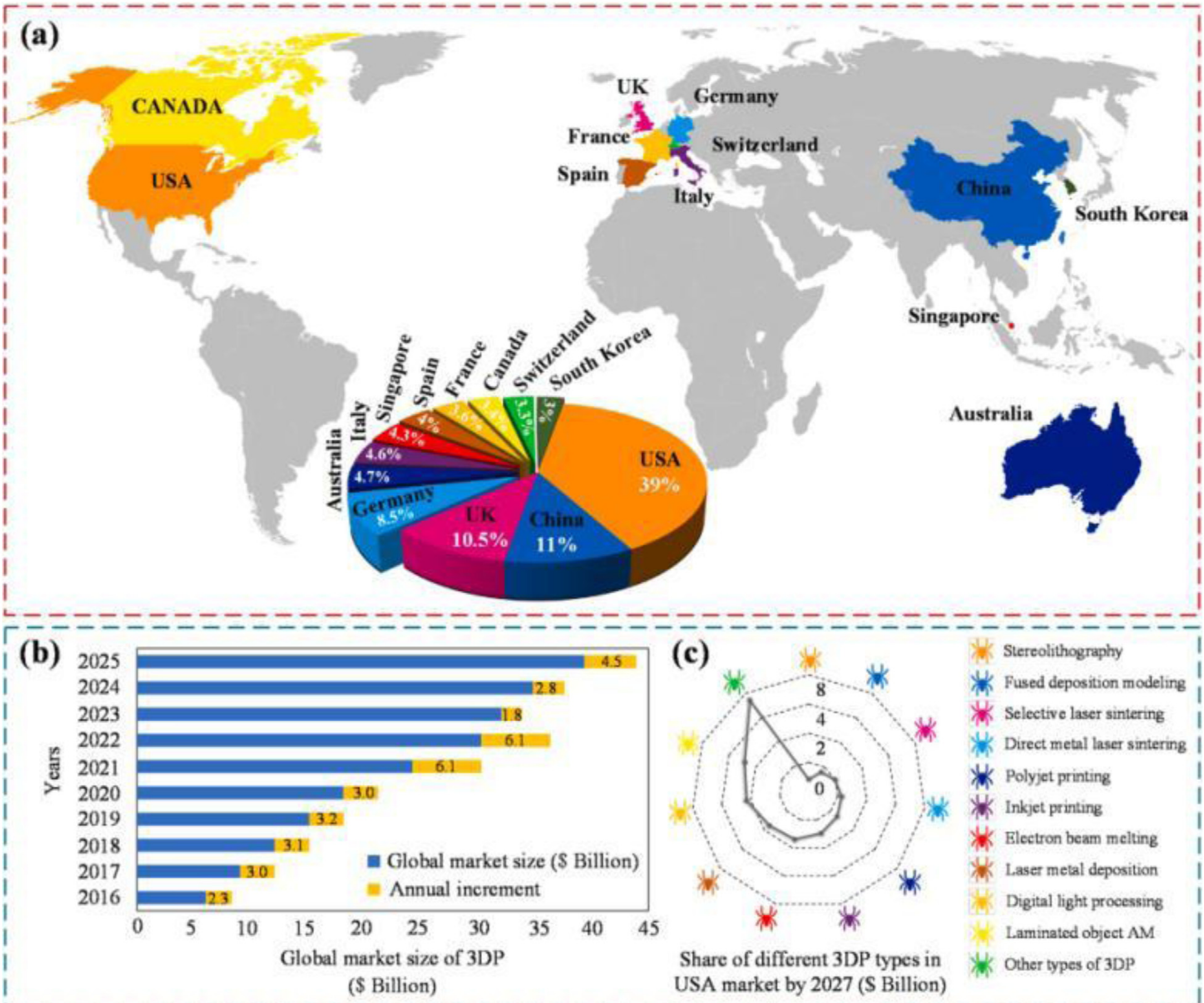

Fig. 3. Global outlook of AM technologies showing: (a) Research intensive in developed countries, (b) Yearly distribution of milestones and global market share in US dollars and (c) Estimated market share of various AM techniques in the United State market by 2027 [64].

the 3D printer to carry out a task. There are various steps to achieve the GCODE and is dependent on the type of AM method. For instance, by uploading the STL-file in the printer, the GCODE can be generated automatically. A GCODE is easily automated to aid mass production. The 3D machine is then set up and configured with the right parameters such as energy source, timing, and surface thickness prior to printing. The as-fabricated part is cleaned and the right postprocessing technique done. This could range from microstructural to mechanical characterization and certification.

4 Global trends and state of additive manufacturing research

Global research, innovation and development around AM or 3D printing is summarized in Figure 3. The United States contributes ~39% to global outlook with China being the second with ~ 11% (Fig. 3a). The AM technology is rapidly growing with global market size estimated to grow by 25–30% by 2025 and estimated value at US$ 40 Billion. The overall contribution to market share per year since 2016 is given in Figure 5b. As of 2019, at least 1.5 million well equipped 3D printers were distributed and being used by various industries and academia [64]. The number is estimated to increase to ~8 million by 2027. This lay credence to the increasing research and development supporting the 3D industry and the advantages associated with 3D printing, which is additive in nature compared to most of the subtractive manufacturing processes (Tab. 4) [4,64,97]. These merits of AM over conventional subtractive methods are based on cost, time, resource consumption, product complexities, post fabrication processing and treatment, material quality and structural integrity, waste, prototyping, and general applications.

Additive manufacturing in distributed manufacturing systems is found in cloud manufacturing. This is a customer-centred fabrication model for on-demand access to diversified and distributed manufacturing

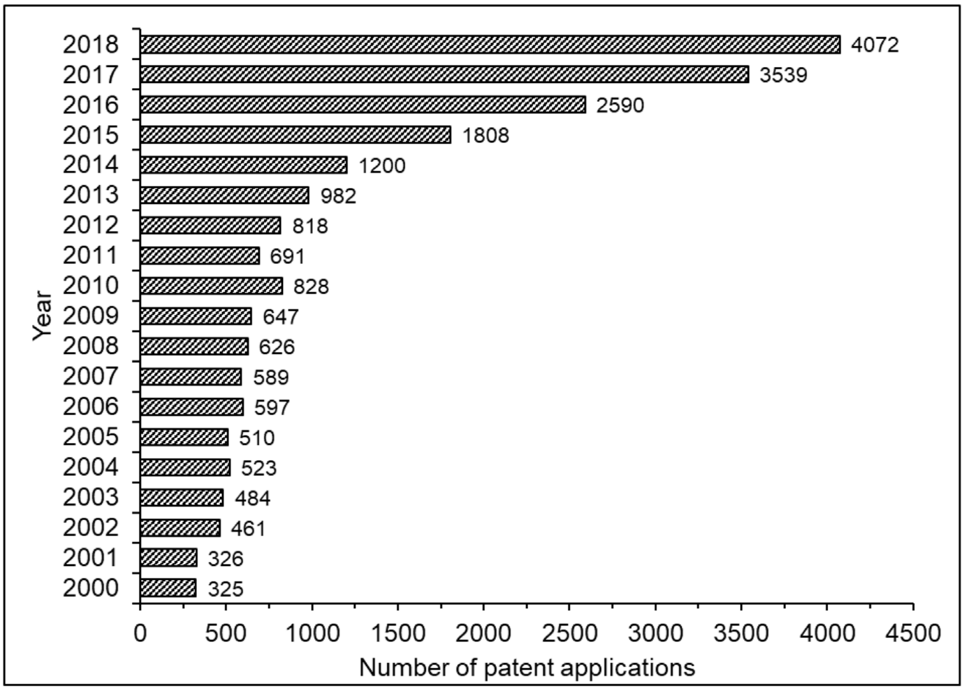

Fig. 4. Annual patent applications globally from 2000 to 2018 [65].

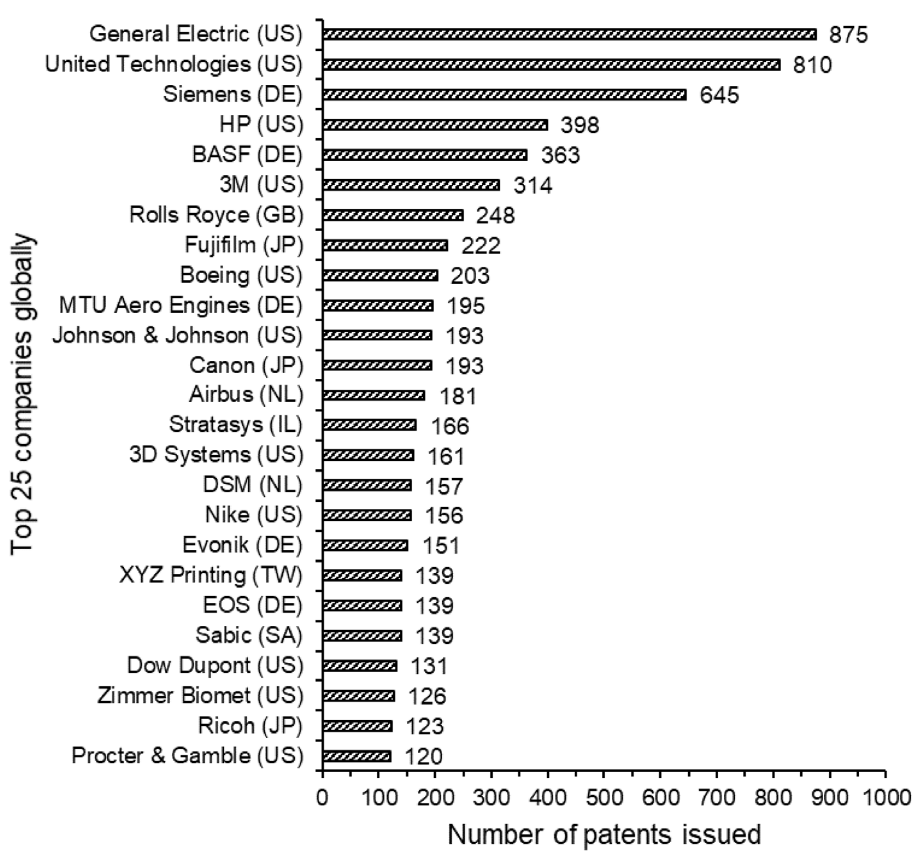

Fig. 5. Top 25 global companies and the number of patents approved [65].

Table 4. Comparison of the benefits of conventional and AM techniques [4,97].

Conventional manufacturing	AM or 3D manufacturing
Cost: Extremely expensive for miniaturized samples due to various steps involved such as moulds, dye, tooling, and other post-processing techniques that results in final finishing.	Many of the products can be fabricated at low-cost especially for small sized materials.
Waste: Material wastage is extremely high as most of the techniques do not result in near-net shape. For instance, in casting, gating systems and risers must be machined from the actual component.	There is limited waste of materials as the process is additive and final component is fabricated to near-net shape, thus less machining is required.
Prototyping: This is not really designed for rapid prototyping hence very time consuming and expensive. It is not an ideal process for concept designs and prototypes.	This is prototypically oriented and excellent concept for evaluating concepts design and iterative processes to arrive at components with optimized properties.
Product complexities: This is difficult to manufacturing complex geometries and product with intricate parts specially for casting where complex patterns will generate blowholes, which is very detrimental to overall structural integrity.	This is very ideal for complicated and complex geometries. Once the shape and its intricacies can be conceived, it can surely be fabricated especially by being able to design the digital twin.
Post manufacturing treatment: This requires some form of processing after fabrication. This could be machining to the desired shape or cold and hot working to induce respective properties.	This is dependent on the technique and the material being used as some do not require any post-fabrication processing.
Structural integrity: Components from these techniques are for load bearing applications due to the high densification associated with them post fabrication.	This is dependent on the material and the techniques being use. They are widely used for functional and some structural applications. With the current evolution and rapid advancements, there is great strides in excellent structural integrity.
Resource consumption: This is extremely high and extremely costly.	Being an additive procedure, the material usage is optimized to fabricate components.

materials for adaptable manufacturing lines [98,99]. This cloud based AM applications have been used in manufacturing tailored sport wearables, on demand production of vehicles and motorcycles [99]. These have changed the traditional supply chain models and production lines making the additive manufacturing to be a promising Industry 4.0 technology. This has allowed for remote access to manufacturing platforms and plugins to create a seamless process, creating a network of cloud-based manufacturing, thus reducing overall manufacturing costs.

Additive manufacturing technologies contribute to the reduction of the global carbon emission footprint [64]. These technologies also contribute to overall energy utilization in the manufacturing sector with a positive outlook on global resource productivity. This manufacturing technology eliminates the need for assembly lines and supply chains. This is because many of the processes use single process approach to manufacturing of final components to near net shape. Thus, by sending the digital twin file via email, there will be no need for shipment with its associated tariffs. With this smart manufacturing process, products or components are manufactured on demand and no need to keep inventories for parts. The AM/3D printing is estimated to be US$ 250–550 billion market in the next three to five years. The main sectors of the industrial landscape are in the areas of low volume, customizable and high-value products.

The AM technology relies on some of the advanced digital technologies resulting in the active and intense research throughput globally. This is demonstrated by the exponential increase in patents being filed as shown in Figure 4 [65]. For about 325 patents granted in 2000, the figure had increased to 4072 in 2018. This is due to accelerated change associated with various AM innovations targeting specific industrial applications. Between 2015 and 2018, 3D printing patent applications grew by a yearly average of ~36%. This is at least ten times faster compared to the yearly growth of patents applications lodged with the European patent office in the same period. The largest share of patent application (50%) is associated with new industrial application of AM technologies. About 38% is associated with development and improvements of processes and machines, whereas ~26% and 11% account for material design and digital technologies, respectively. With the infusion of AM technologies in various aspects of healthcare and medicine, the figure is expected to increase significantly from 2019 to 2022.

The AM technology and processes has diverse players. About 25 companies account for ~30% of all patent applications lodged globally. Most of these companies and industries cut across sectors such as chemical and

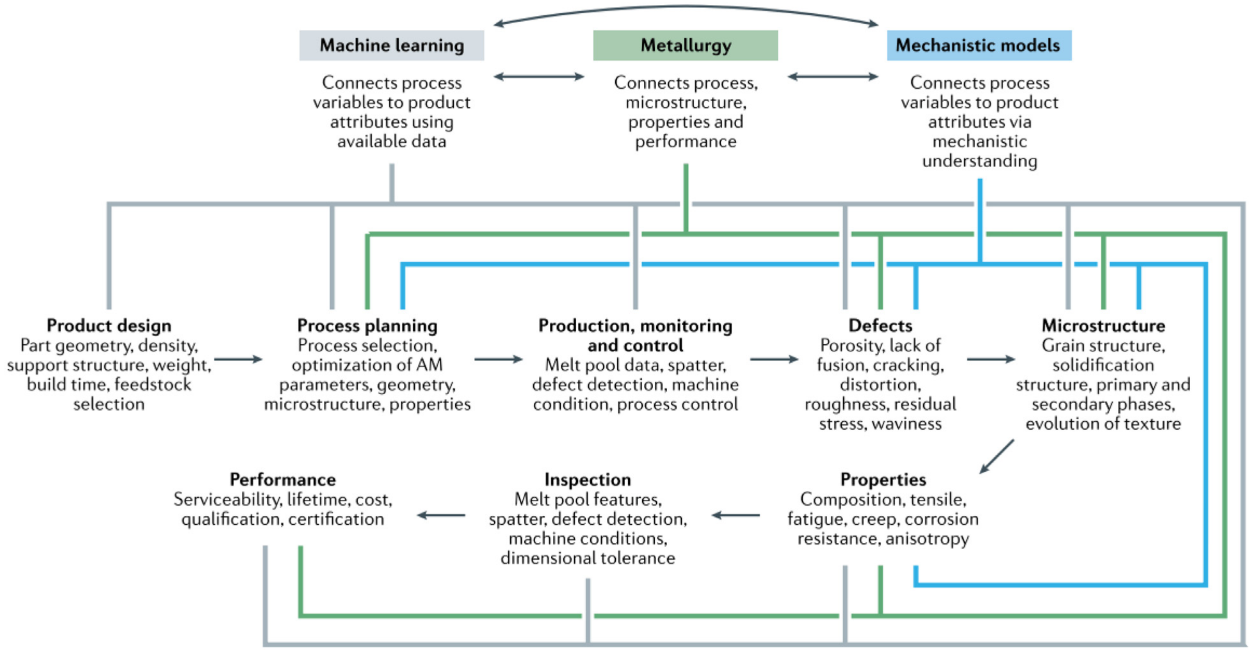

Fig. 6. The interplay of machine learning and mechanistic models in understanding the physical metallurgy of AM processes and techniques [100].

pharmaceuticals, information technology, transportation (aerospace and automotive), electronics, consumer goods and imaging (Fig. 5). The United States and continental Europe are the major global players. The former has about 11 major companies and eight for the latter. German companies account for about 63% of the European companies in the top 25 from 2010 to 2018. There is no African company featured in the top 25 companies. Africa is less industrialized continent and less than 5% of continental gross domestic product is allocated to driving innovation, research, and development. Africa consumes what it does not produce and produces what it does not consume.

There has been increased installation and geographical distribution of 3D printing industrial systems globally. Between 2010 and 2018, ~37% of industrial systems were installed in North America, 28.4% in continental European, ~30% in Asia and the Pacific and ~4.6% for the rest of the world. The pervasive nature of the technology is due to massive use by most of the world leading industries. There are enormous resources dedicated to research and development that are industry driven. This has led to strong industry-academia partnership bridging the gap between the two. New insights from research centres, university laboratories and industry inform the applicability and acceptability of the technology.

4.1 Multidisciplinary dimension of additive manufacturing

Additive manufacturing connects the metallurgy of materials with machine learning and mechanistic models [100]. This is illustrated in Figure 6 providing an overarching understanding of the connectedness of the multidisciplinary approaches to this smart manufacturing method. The synergetic contributions of machine learning, metallurgy, and mechanistic models, following a rational alloy design model of the various steps in the production and characterization of parts are highlighted. The physical metallurgy defines the process parameters required to achieve desired microstructure to induce the design properties to meet the intended application. Machine learning processes are data-driven, and knowledge guided decision-making tools which prevents trial-and-error design concepts. The mechanistic models apply theory and sound scientific judgement based on process parameters to simulate and optimize process parameters and conditions under which additively manufactured components can be used (Fig. 7). In metallurgy, the relationships between process, structure, properties, and performance are complicated and not easily quantifiable. A quantitative framework for understanding the metallurgical characteristics of individual parts can be provided by mechanistic models and machine learning techniques.

In a typical mechanistic simulation, the prediction of residual stresses, defects, microstructural features such as grain texture, sizes and structure are functions of input and process parameters as well as the properties of the base material (Fig. 7) [101]. These phenomenological and mechanistic models require in depth understanding of the typical AM technique as it varies from process to process. The flowability of the powders, mass and heat transfer analyses of a molten pool and the interaction of the surroundings rely on the transient conservation of mass, energy, and momentum.

Based on increasing research in AM technologies, recent research topics are in the niche research areas of condition monitoring, sustainability [102], environmental degradation [103], defect assessment on structural integrity

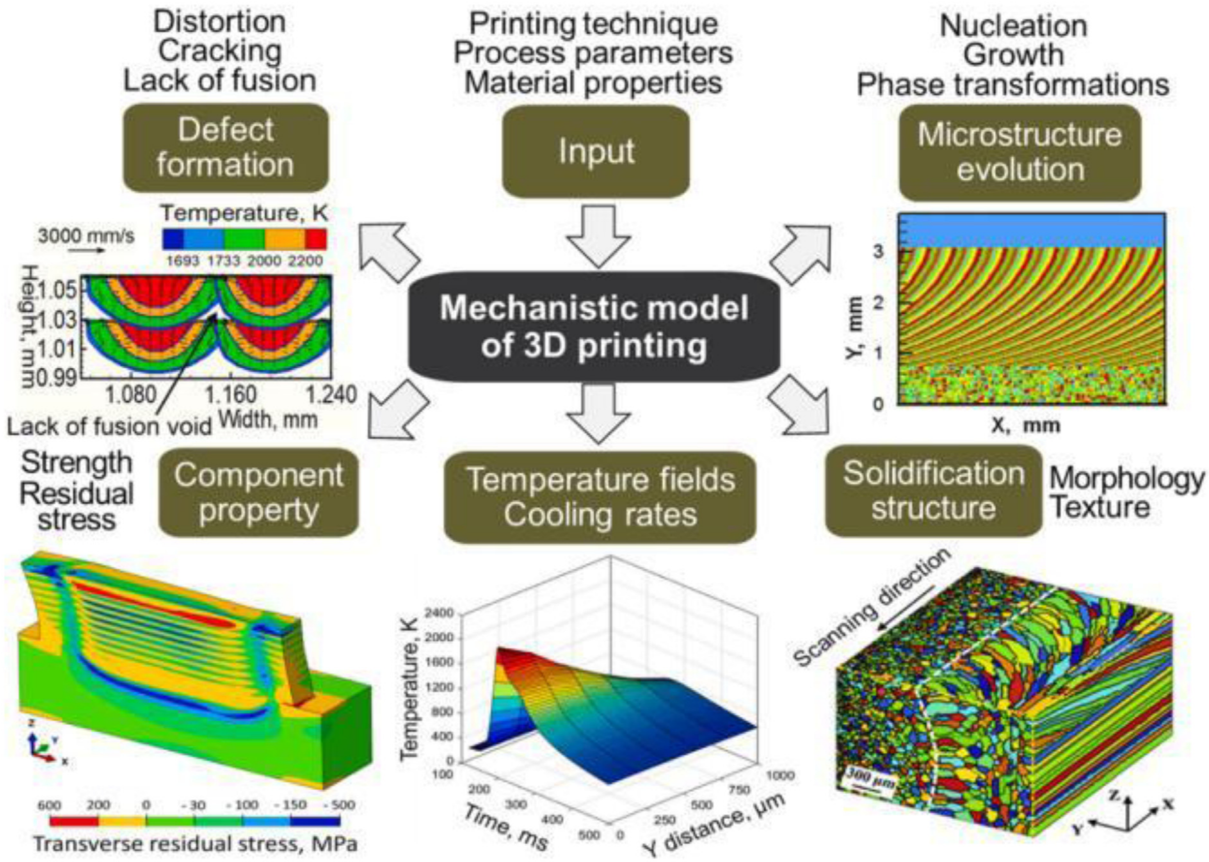

Fig. 7. Mechanistic models for fluid flow, heat, and mass transfer for a typical additively manufactured metallic component [101].

[104], optimization of process parameters on different AM processing techniques and suitable material choices. Recent authoritative reviews focusing on the introduction of material-structure-property-performance of additively manufactured components have also been discussed [95,100]. The infusion of big data analytics into various classes of AM technologies and design parameters have also been reviewed across various high-value and low-volume components in the aerospace, healthcare [105] and construction industries [104]. An overview of classes of materials, applications, shortcomings, and benefits for various 3D/AM techniques is given in Table 5 [89].

The use of 3D printing technologies to produce various components and final parts in the various industries are given in Table 6 [65]. These industries are aerospace, energy, biomedical (medical and dental), motor vehicles and footwears. As an emerging and fast-growing technology, the prospect for fabricating many parts and components is inexhaustive and incomprehensible.

4.2 AM applications in medical and biomedical application

4.2.1 Medical devices and biomedical applications

The healthcare industry is one of the main domains where 3D printing is highly utilized. This is being actively used for the manufacturing of medical devices [10–40]. This is advantageous especially for most of the AM applications in medicine as there are so many intricate shapes and geometries which are easily printed [10]. The 3D printing process is an easy way of fabricating medical devices and instruments that are patient-specific and need-based [106]. Medical applications of 3D printing can be categorised into anatomical models, tissue and organ fabrication, customised prosthetics, patient-specific orthopaedic implants, and pharmaceutical research [107].

A typical timeline for the applications of 3D printing in medicine since its inception from 1984 to 2020 is given in Figure 8. Thus, 3D printing has been successful with continuous improvement on processing parameters, microstructures, and overall performance through material-structure-performance optimization. The technique has evolved resulting in printing soft and hard tissues [121].

Meta-biomaterials are a promising route for the development of long-lasting implants [122,123]. Mandible implants were fabricated using the electron beam melting using the powder based Ti6Al4V biomaterial with particle size distribution of 50–100 μm. These mandibles were customized and tailored to the intricate geometry of the bones of patients. This reduced the pre-surgical planning and hands-on practice in fixing the screws with precision on the implant. Electron beam melting was used to fabricate implants to replace a defective Talus bone [124]. The implant was further coated with wear-resistant titanium oxide surface layer and currently at human trial stages.

Table 5. Overview of classes of materials, applications, shortcomings, and benefits for various 3D/AM techniques [89].

Materials	Major applications	Benefits	Drawbacks and shortcoming	References
Polymer & composites	Aerospace Automotive Sports & recreation Architecture Biomedical & Medical	Fast and rapid prototyping Fabrication of complex structures Mass customization of printed components Cheaper than conventional methods	Selection of limited materials Dimensional inaccuracy of finished product Post-processing is needed (heat treatment, chemical etching, and machining of parts	[87–91,95,100, 108–110]
Metals and its alloys	Automotive Military Biomedical Aerospace	Optimization at a multifunctional level Mass customization of printed products Reduction in overall material wastage Few assemblages of unit parts Material repair of worn parts	Selection of limited materials Dimensional inaccuracy of finished product Post-processing is needed (heat treatment, chemical etching, and machining of unwanted parts	
Ceramics	Biomedical Aerospace Automotive Chemical industries	Great control of lattice porosities Printing of scaffolds for human organs Decreased time for overall fabrication Control of composition and microstructure	Constraints based on material selections Poor surface finish Dimensional inaccuracy of finished product Post processing technique, e.g., sintering	
Concrete	Infrastructure Construction	Mass customization No formwork required Less need for labour especially for space construction and harsh environment	Layer-by-layer appearance Mechanical properties are anisotropic Inter-layer adhesion is poor Upscaling for big buildings is a constraint Few 3D printing methods available	

Table 6. Industries and typical components that are fabricated using AM [65].

Industry	Mechanical parts and components being fabricated	References
Energy	Rotors, turbine nozzles, stators, down-hole tool components and models, flow meter parts, pressure gauge components, pump manifolds, control valve components and mud motor models	[60–62]
Biomedical/ medical	Orthopedic and dental implants, implants for skull disorders and facial reconstruction, dentures, bridges and crown copings, artificial human organs (heart, kidney, and pacesetters.	[17,18,19–26,113–118]
Motor vehicles	Spare parts, joint of chassis and shell parts for body of motor vehicles	[87–91]
Footwear	Heels, insoles, customized footwears, and midsoles	[119,120]
Aerospace	Plastic brackets, clips, actuators, hydraulic systems, metal fuel nozzles, pipe elbow for fuel systems, turbine blades, aircraft parts, ducts, cable stays, filters for communication satellites, Ti- and Al-based parts	[87–91,95,100,108–110]

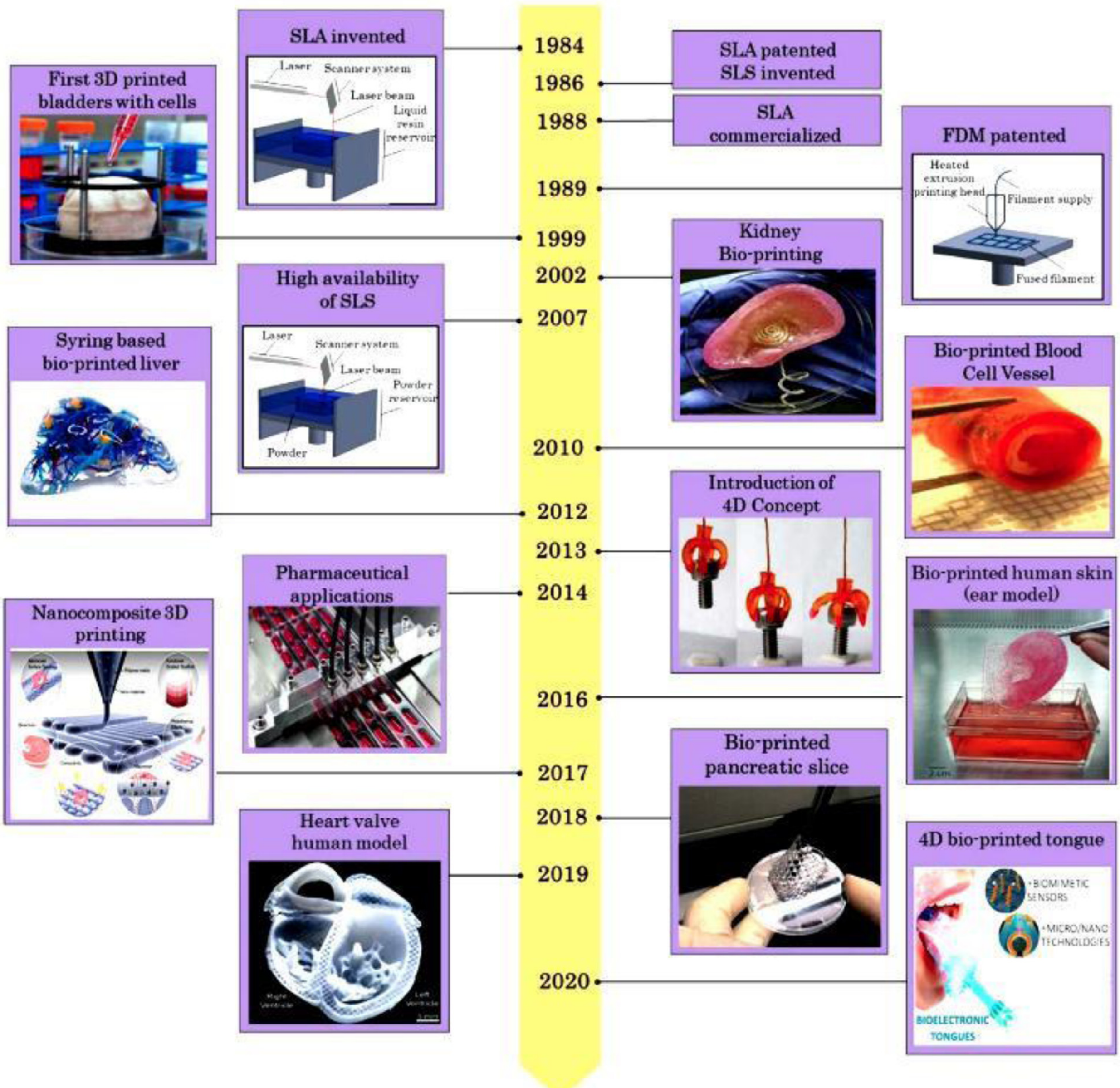

Fig. 8. Timeline for the application of AM and bioprinting techniques in the medical field [129].

Fatigue behaviour of laser powder bed fusion printed auxetic meta-biomaterials from titanium showed morphological and mechanical properties were compatible and appropriate for bone replacement [125–128]. The designs conformed to the intended geometry.

AM techniques have been used to design micro-needles master moulds [130]. The open-source computer-aided design software and HTM 140M acrylate-based with polydimethylsiloxane (PDMS) silicone elastomer as moulding material were used [130]. The micro-needles were effective for skin penetration without pre-mature fracture due to higher fracture force than the insertion force. Based on the AM technique, tips and angles of the micro-needles were carefully designed to be very sharp for improved skin penetration.

For tissue and organ printing, the main factors are around hardware (scanners and printers) [96,131–135], software (AutoCAD, 3DS Max, Solidworks, Ansys, Rhino, Fusion 360) [96,136–138], biomaterial (metals, polymers, composites, and ceramics) [41,96,139–146] and bioink (ability of the AM part to be able replicate properties of a human tissue or bone or living cell) [23,32,96,147]. Detailed applications of various AM/3D printing approaches used in various aspects of medicine is given in Table 7. Human organs, skins, cells and various vascular tubes with intricate shapes, soft and hard bones have been printed using 3D and successfully implemented. Materials used for these processes are metals, polymers, ceramics, and composites. One of the successful application is the remedial spinal surgery using the technology [59]. Omental

Table 7. Advances of 3D printing in the medical industry.

Area of application	Detailed description and milestone	References
Human organs (heart, liver, kidney, and its tissues)	Near net shapes and sizes of various human organs ranging from hearts, livers, kidneys and its related tissues, ventricles, chambers, and cells have been printed. 3D printing gain momentum for reconstructive medicine and regenerative surgery as well as therapy	[11–16,18,20–26, 31,32,147,178–180]
Human skin and cell printing	Printed skin grafts for burn victims and cancer patients. Some of these printed skins have been implemented successfully on patients with no adverse side effects. Various human cells and tissues have also been printed and successfully implemented. These cells have the regenerative properties of a typical human tissue and cells, which is due to the materials used for the process.	[17–26]
Vascular tubing	Hollow vascular tubes are fabricated to the required sizes and shapes for cells and biological matrices and scaffolds. One of the best methods for complex and intricate human vascular tissues.	[27–33]
Bones and its related tissues	3D printing of various soft and hard bones of the human body has been successful.	[34–40]
Spine surgery	3D printing is gaining traction in spinal surgery, from anatomical models to surgical tools (screw guides and customized inserts and implants).	[59]
Orthopedic Applications	AM has been successfully applied for surgical instruments anatomic models, tools, prosthesis, and orthopedic implants (spinal devices and knees).	[113–118]

Table 8. Standard ISO, ASTM and NASA certifications and protocol for additively manufactured products and technical know-how for aerospace applications [2].

Certification name	Description
Full operational	
ISO/ASTM F3434-20	Installation, operation, and performance assessment for Laser-beam PBF equipment for component manufacturing
ISO/ASTM 52942-20	Standard for qualifying machine operators of Laser-beam PBF for aerospace applications
ISO/ASTM 52941-20	Acceptance tests for LM PBF machines
Standards under development	
ISO/ASTM AWI 52937	Qualification for designers
ISO/ASTM CD 52920	Quality requirement for industrial additive manufacturing
ISO/ASTM CD 52926-1	General qualification framework for AM machine operators
ISO/ASTM CD 52926-2	Qualification framework for machine operators – PBF LB
ISO/ASTM CD 52926-3	Qualification framework for machine operators – PBF EB
ISO/ASTM CD 52926-4	Qualification framework for machine operators – DED LB
ISO/ASTM CD 52926-5	Qualification framework for machine operators – DED ARC

tissues were obtained from human to produce a thermo-responsive hydrogel, which was used as a bioink for 3D printing of vascularized and perusable cardiac patches [121]. Artificial heart valves have been 3D printed from biocompatible silicone with tuneable mechanical properties using spray and extrusion-based additive manufacturing technique [148]. Outstanding hemodynamic performance of the valves under physiological pressure conditions based on cyclic testing was achieved. The bioinspired designs proved to be an effective approach for controlled differentiation and growth of cells in tissue-engineered constructs.

The material property requirement of these materials being used as biomaterials ranges from biocompatibility [33,139,146,149–160], good mechanical, corrosion, and physical properties closer to the part of the human bone or tissue being replaced [113,139,140,146,155–157,161–174]. There should also be some level of porosity for good cell attachment and great connectivity while interacting with the human cell and to ensure tissue growth and soft tissues such as cartilage, tendons, vasculature, and the skin [175–177,181–186].

4.2.2 Additive manufacturing in response to the corona virus pandemic

The role of materials science and engineering in healthcare has always been apparent since the dawn of civilization (Fig. 9). As a hot topic in physical metallurgy of material processing, AM has instrumental in the response to pandemic [64]. This has been attributed to the ease of adaptability of digital manufacturing and the rapid prototyping for swift response to the pandemic [129,181–186]. It was a strategic manufacturing approach to meet the surge in emergency medical supplies at the peak of the pandemic. Though the pandemic disrupted and halted continental supply chain business, AM technologies enabled regional production of parts using a typical CAD (Computer Aided Design) design software, which are available in most universities and research centres. Manufacturers and research universities were proactive in filling the gaps in healthcare equipment for medical professionals and patients all over the world. The quick and mass production of emergency use authorization (EUA) medical devices and equipment were successful due to the use of AM processes.

The wide spread of AM technologies in response to corona virus pandemic were in design and manufacture of personal protective equipment (PPE), diagnostics and testing, development of medical devices, emergency hospitals and dwellings, and visualization aids [64]. Devices such as face shields [64,182], PPE, respirator valves, low-cost ventilators, and ventilator parts [39–43]. Quality and certified medical devices such as prosthetics, trachea splints, scaffolds, implants, maxillofacial and microneedles have been designed and printed [39–43]. The soft lithography-based fabrication of microneedles (MNs) is a cost effective, easy, and fast method with variable designs compared to conventional manufacturing techniques [39–43]. Thus, a flexibility associated with 3D printing due to the layer-to-layer deposition.

Additive manufacturing is a straightforward process which reduces iterative and repetitive processes with conventional manufacturing process. This is what was instrumental in reducing the shortfall of medical devices to combat Covid-19 [183,186]. With the ease of operation and simple components of most AM machines, universities and research centres could install desktop types and use them to design and print various medical devices amidst nationwide lockdowns.

A fully functional face shield was made in less than 45 mins per initial trials [64]. This is further optimised for exceptionally low time (~15–20 min per shield) using a fusion deposition method (FDM). The AM technology is fit-for-purpose for the healthcare industry [36–40]. The AM technologies can easily be tailored and automated for mass production especially in this era of smart manufacturing. This technology is at the frontier of big data analytics and the internet of things where digital twins and replicas are essential and critical.

4.3 Additive manufacturing in aerospace industry

Additive manufacturing is used for manufacturing of high-value aerospace components [95,100,108–110]. This promotes reduction in lead time while lightweight structures with complex and intricate parts are easily fabricated with great functional properties and performance. Lightweight structures are critical from techno-economic and cost management perspectives. The low-volume and high-complexity of structures are inherent in the numerous parts that need to be designed and manufactured separately before assembled into systems and subsystems to drive the right functionality and performance. This is shown by an artistic impression of a typical 787 Dreamliner structure supplier and respective parts with companies and countries (Fig. 10). Each component is designed to take advantage of its functional properties and performance be it flow, durability, reliability, compatibility, and structural integrity.

Materials usage in the design of a typical aerospace components are metals, polymers, composites, and ceramics. Metallic components are produced from Al-based, Ti-based, specialty steels (stainless steels), Cu-based, refractory-based, Ni-based, Co-based, and Fe-based superalloys. Composites include carbon fibre reinforced polymer composites. These materials are used in the pre-alloyed powder conditions or wire based on the fabrication route. Some of the commercially Ni-based alloys for 3D printing include Inconel 625 and 718, Hastelloy-X, Haynes 214, 230 and 284, Monel K-500, Rene 80 and Waspalloy. The Fe-based alloys include precipitation hardening stainless steel, austenitic stainless steel grades 304L, 316L and 347 and invar 36. The Ti-based alloys include Ti6Al4V, ɣ-TiAl and Ti-6-2-4-2. The Co-based alloys include CoCr, Stellite 6, Stellite 21 and Haynes 188. The application of these alloys is driven by design and property criteria.

Extensive reviews of aerospace components manufactured using laser powder bed fusion (LPBF) and LDED are given. These include thrust chamber from Cu alloys, reflector brackets, aircraft door locking shaft, aero-engine,

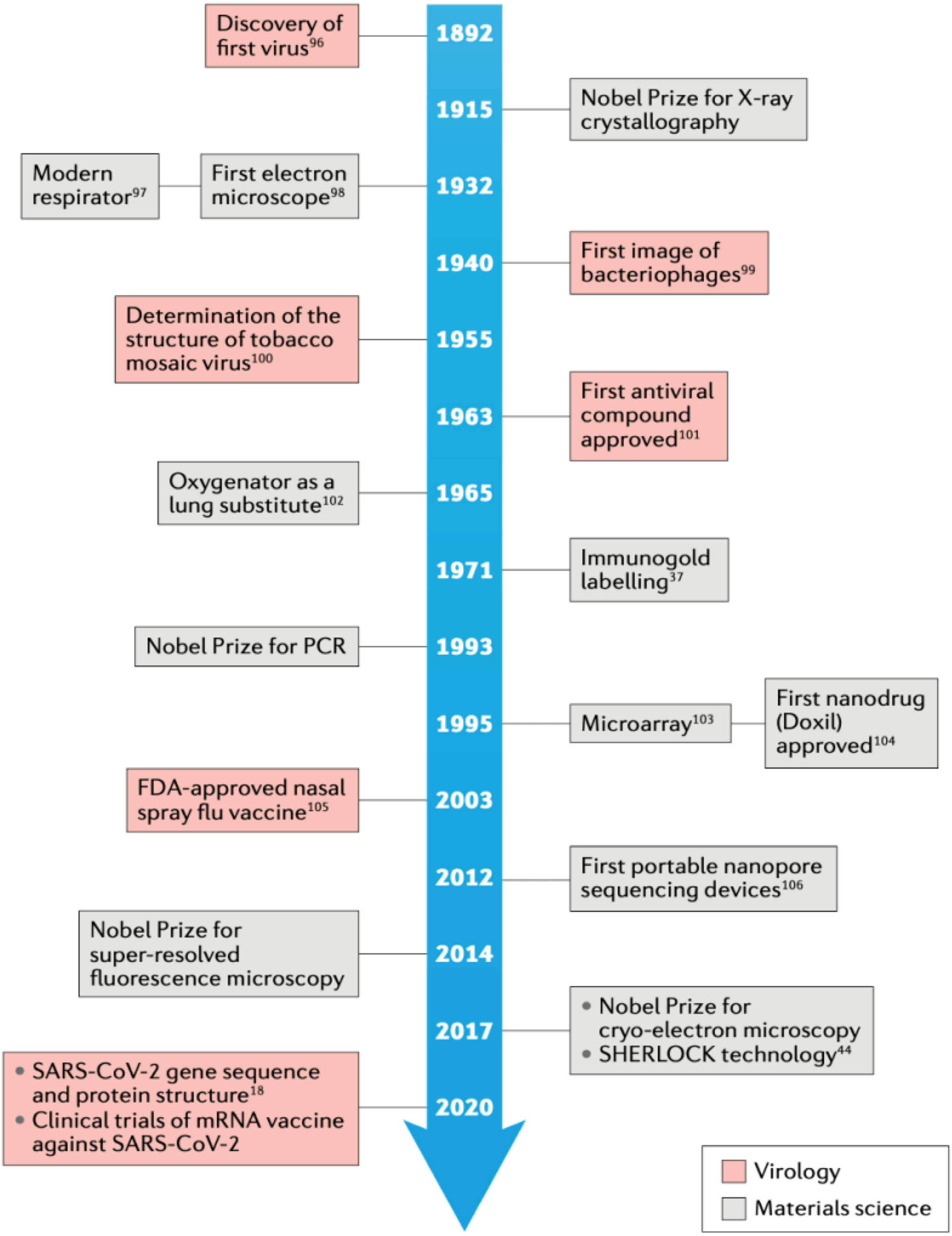

Fig. 9. Contribution of materials science and engineering to medicine [181].

Fig. 10. Artistic impression of a typical Boeing 787 Dreamliner structure supplier showing intricate mechanical components that is assembled into a fully functional aeroplane.

combustion chamber for rockets, rocket engine injectors, turbine blades, sentinel antenna bracket, tracker bracket, hydraulic manifold, and combustion chamber for helicopters, just to name a few. Recent advances in Laser-based AM technologies have provided beneficial and cost saving due to the integrated manufacturing (Fig. 11). There is no need for assemblage of parts as multimaterial can be printed with ease. Examples include metal-matrix composites (MMC) [110,187–190], gradient and hierarchical materials, in situ composite or nanocomposites [2,110,191,192], topological, lattice and biomimetic structures.

Recent approach is the infusing of the material-structure-property concept for the design of planetary lander for space exploration (Fig. 11) [95]. This incorporated the harsh and aggressive corrosive environment of the outer space into the design process (Figs. 11B and 11C). By applying hierarchical additive manufacturing processes complimented by conventional manufacturing such as forging and welding the designed multifunctional component is achievable. This is expected to be a game changer and the new paradigm for innovative AM strategies, especially for aerospace applications.

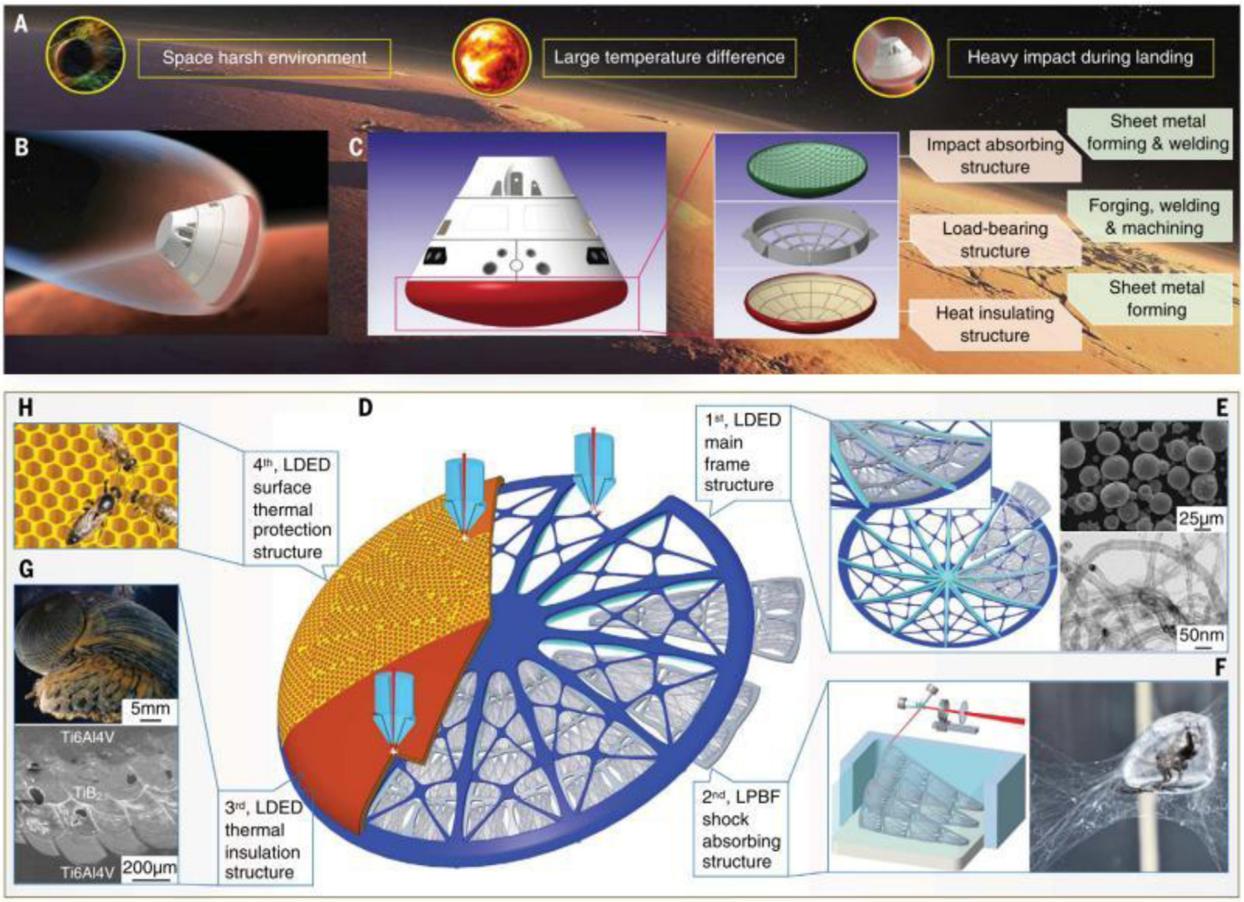

Fig. 11. Typical example of a material-structure-property integrated AM manufacturing for a lander for planetary exploration: (A & B) are schematics of the lander and under extremely harsh condition during landing, (C): conventional hierarchical manufacturing and assembled bottom part with multifunctional requirement, (D to H): the material-structure-property AM approach for multifunctional design of the parts [95].

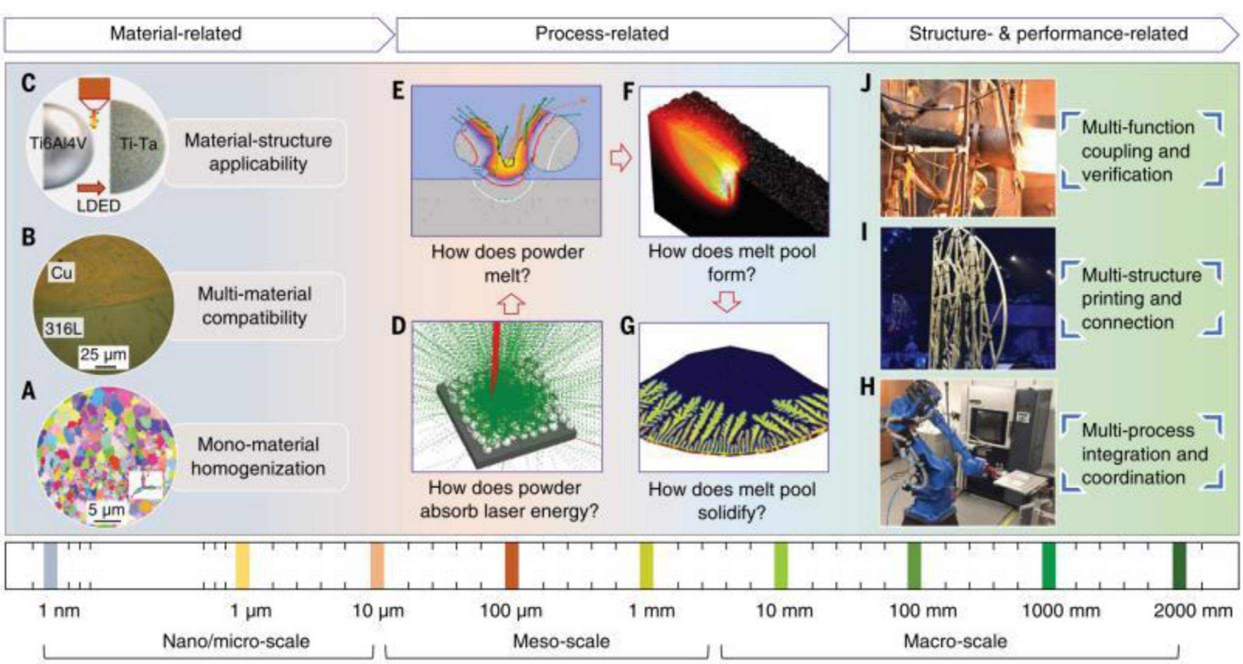

Fig. 12. Typical material-process-performance driven 3D printing paradigm.

For the lander for planetary exploration, the material-structure-property approach entails the selection of the several types of materials, required structural features driven by processing routes to enable optimum performance. Typical example focusing on integration of required structures and materials, which are performance-driven design of hierarchical structures with dissimilar materials; the integration of multi-process hybrid manufacturing and integrated conventional manufacturing while focusing on the overall performance of the lander machine is summarized in [95]. A schematic of material-process-structure-performance approach through the various microstructural and length scale is given in Figure 12.

4.4 Additive manufacturing in emerging energy and electronic devices

The world is in a massive state of energy crisis coupled with increasing use of fossil fuels with global climate implications [111]. The utilisation of fossil fuels has doubled since 1974 according to the International Energy Agency (IEA). At the current consumption rate, the overall fossil fuel reserves would be depleted by the next 100 years [193]. This has necessitated the drive to reduce the over dependence on carbon-based fossil fuels while introducing renewable energy resources into the global energy mix [60–62]. This is expected to reduce the greenhouse enormously. These initiatives are achievable by developing low-cost energy-storage and conversion devices using emerging technologies such as the 3D printing [60–62]. Using the 3D printing approach, the usable life of these batteries and supercapacitors can be increased while using low-cost materials instead of catalysts and electrolysers from expensive platinum group metals, especially with the advent of current water splitting technologies [63–70,194–201].

Additive manufacturing has been used to fabricate turbine blades for various energy harvesting applications. Selective laser melting was used to design a graded lattice structures to replace the internal solid volume of turbine blades [202]. Through the 3D printing process, there was ~33.41% to 40.32% reduction in weight of the turbine blade, stress rate 25.52% to 48.55% and ~7.35% to 19.58% deformation rate. Design and optimization of the turbine blades lattice structures through SLM 3D printing process, has increase the ability of the turbine blades to endure high thermal stresses effects. The result has confirmed the efficiency of producing an intricate part such as lightweight lattice structures of turbine blades through the SLM process. This would have been difficult to manufacture through the conventional methods because lattice structures obtained by the topology optimization technique are very irregular [202].

Similarly, small wind turbine blades were fabricated using AM techniques [203]. The blades were printed using PLA plastic with consistent blade geometry which was also cost effective (~R150 to R500 per blade). Wind speeds of ~32 km/h on average and rotational speeds of over 500 rpm was observed.

Computational 3D printing based on Digimat-AM techniques have been used to developed a new small-scale tidal turbine blade [204]. The Digimat-AM tool was used to simulate different configurations and to evaluate the performance of parts fabricated by 3D printing. Thermoplastics polymers polyamide 12 (PA12) and polyether ether ketone (PEEK) were the materials of choice for printing the turbine blade. Finite element simulation was carried out to determine the Von Mises residual stresses and temperature field.

A 3D printing a γ-TNB turbine blades from elemental powders of Ti, Al and Nb via 850-R Optomec LENS machine have been done [205]. The detailed experimental set-up can be perused. The study revealed hardness of the as-built sample was higher than that of the heat-treated sample. The higher hardness in the as-built sample can be traced to the distinct phases present in the grain, microstructures, and lamellar growth. Also, deformation was observed on the misaligned and globular lamellar microstructure.

The 3D printing technique has been used to fabricate various electronic devices [97–102]. For instance, [206] proposed a 3D printer-like data interface for a machining robot. The 3D data interface enables to control the machining robot directly using STL data without conducting any CAM process. This is done by developing a robotic pre-processor that removed the conventional CAM process by converting directly the STL data into CL data. This unique machining system is tested and validated using actual machining experiments.

Current advances in communication devices and radar technology have benefited from 3D fabricated components [207]. A megastructure based on graphite SLS composite was designed for radar absorption. The design was based on a three-layer consisting of a cross-shaped surface structure, square block middle layer and conventional single slab bottom layers. The structure had a reflectivity below −10 dB with frequency ranging between 7.6 and 18.0 GHz at normal incidence of waves for transverse electric and transverse magnetic waves. The absorber with impedance matching air resulted in minimized reflection and subsequent broadband absorption [207]. The proposed RAMS demonstrate polarization insensitivity and cost-effectivity as it is made from commercially available 3D printing material and technology. Similarly, typical Ku-Band lightweight aluminium waveguides fabricated by direct metal laser sintering process with promising properties [208]. Bayesian networks coupled with 3D printing have been used to develop fault diagnosis in additive manufacturing processes [209]. All these revolutionary designs of electronic equipment are necessitated by the merits associated with AM technologies.

4.5 Additive manufacturing in building and construction

The conventional construction methods relied on replica models to design and construct structures. These models are in two dimensions and are being transitioned to 3D models driven by the building information modelling (BIM) tools [48–50]. The application of AM in construction industry is synonymous to using architectural design tools to produce small and mega structures, walls, and façades of buildings [50,51]. This transition to 3D BIM tools is due to recent drive towards automation, reducing in cost overruns and overhead costs, and reduction in completion time [50–54]. For instance, the cost of printing a house is the same as printing a concrete block [55,56].

The BIM system contains wide range of information such as equipment, resources, materials, and manufacturing data to aid any structural design and fabrication in the building and construction industry [210–213]. This is advantageous for easy automation especially for mega structures with so many intricate parts with the need for extreme attention to details [45]. Automation in BIM systems contributes to overall reduction in lead time of the project as other individual steps can be integrated easily [50,51]. Thus, the BIM is comprehensive tool for critical assessment and evaluation of building and construction life cycle [50,51].

The three main forms of 3D printing in the building and construction industry are concrete printing, contour crafting [55,56] and D-shape [47]. These are all based on layer-to-layer fabrication techniques which can be automated. Concrete printing is the 3D printing of structures such as buildings and houses using an extrusion process. The two type of concrete printing AM machines are the six-axis robot and four-axis gantry [45]. The four-axis gantry is suitable for printing megastructure due to its ease of operation and simplicity.

Technical and operational issues of the 3D printing process lack of awareness and deep appreciation of the technology among stakeholders are the barriers to the adoption of the technology in construction industry in Africa. However, there have been some progress on the use of the technology on small scale. For instance, a small-scale pilot approach for hybrid 3DP in wall building was experimented in Egypt [214]. This technique is customized to produce a low-cost and sustainable wall in Egypt and then extend to underdeveloped countries. The study offers blueprints for hybrid 3D printing technologies in terms of apparatus design, wall design, printing process, and material content. Another study focused on the effects of nano-silica on the fresh and hardened properties of 3D printable mortars [215]. Despite the different mixture of compositions of mortars and concretes, nano-silica has a substantial effect on fresh and hardened properties of 3D printable mortars.

Some of the successful initiatives using AM processes in industry are 3D Concrete Printing in Loughborough University, Massachusetts Institute of Technology (MIT) Media Laboratory and DUS Architects, Batiprint3D, WinSun Company, Contour Crafting Corp, Andrey Rudenko, BetAbram, Branch Technology's C-Fab, StroyBot, 3D Printed Dubai office building and AMT-SPETSAVIA. Recent success in the construction industry has been the bicycle bridge fully operational in Netherlands. There is also a pedestrian bridge built in Spain.

The majority of existing 3DP applications are industry based [214]. There have been several initiatives by; WinSun Company, Andrey Rudenko, C-Fab by Branch Technology, Dubai's 3D Printed Office Building, Loughborough University's Concrete Printing, Apis Cor On-Site Printing, the MIT Media Lab, and DUS Architects, Batiprint3D, Contour Crafting Corp, BetAbram, StroyBot and AMT-SPETSAVIA. The 3DP technology has also extended its application to bridges; the TU Eindhoven's 3D-printed concrete bicycle bridge [216], and the printed pedestrian bridge in Spain [216–218].

Similar concepts and ways of thinking has been championed by South African researchers and partnering institutions globally [2,51,123,219–232]. Through these efforts more than a dozen publications have emanated focusing on extrusion-based 3D concrete structures [51,229,230,232], X-ray tomography [219,222,225–227, 233,234], biomimicry in additive manufacturing [51,222, 223,231] and critical reviews of AM applications in various industries [2,224].

4.6 Additive manufacturing and quality control assessment

Structural integrity and condition health monitoring is essential for quality control assessment. Quality control and assessment is central and across the entire product life value chain. The structural integrity of 3D printed devices as critical for certification and acceptance of these components, especially medical devices. Hence there are various quality assurance and management agencies across South Africa driving this line of inquiry and research. Preez et al. [235] establishes a quality management system (QMS) for manufacturing certified personalised titanium medical implants using additive manufacturing. This is accomplished using the ISO 13485:2016 quality management system. This accreditation is applicable for designing, developing, and manufacturing patient-specific custom-made titanium implants using additive manufacturing. This contributes to understanding the experimental design techniques using integrated second-order definitive screening design (DSD) and an artificial neural network (ANN) [236]. Modelling has improved AM/3D printing by predicting more accurate and efficient processes. Modelling approaches of each category of different AM processes were performed using key performance indicators: surface roughness, topology/dimensional accuracy, build time, energy consumption, droplet shape, mechanical properties, and microstructure [63,237,238]. These tools are for optimization of operating parameters and variables and to increase the quality of parts manufactured [238]. Critical issue highlighted is about the ensuring the synergy of people, processes, raw materials and machines to ensure that AM components are fabricated of the highest standard [63].

Detailed review of all the certified protocols and standards governing AM technologies and those under development have been consolidated and are given in Table 8. These are by the International Standard Organization (ISO), American Society of Testing and Materials (ASTM), Society of Aerospace Engineers (SAE) and National Aeronautical and Space Agency (NASA). Some of these ISO certifications have been used for quality assessment of 3D printed FDM products [239].

Many ISO/ASTM certifications are being developed for other industries [240–243]. These are being done to ensure quality assessment, evaluation and for benchmarking and guidelines for these standard procedures and the relevant material applications [240–243]. Some of the quality assessment checks focus on dimensional accuracy and microscopic inspections. S-shaped elements revealed dimensional error of 40% while the diameters of the raised circular elements revealed the lowest dimensional error of 0.6%. Dimensional inaccuracies are due to porosity [225]. The relevance of the dimensional error checks is to help 3D printer manufacturers in determining the fast technique for dimensional quality checks. This is important when testing the performance or functionality of a designed 3D printer [225].

X-ray micro computed tomography (microCT) is a non-destructive characterization technique for structural integrity monitoring and assessment of flaws or defects in materials [123,222,226,229,234,244]. The microCT is being used to study effects of defects on mechanical property evolution of structures produced by metal laser powder bed fusion [123,222,226,229,234]. This has also resulted in authoritative review by South African researchers showing that not all defects are harmful and dependent on defect size [234]. Volume defects adversely affect strength and ductility [226,229], which are mutually exclusive especially in traditional dilute materials [245]. Near surface volume defects are detrimental to fatigue properties of AM products [229,234].

Similarly, X-ray tomography characterization was carried out in examining defects and strength relations of additive-manufactured zirconia [246]. Emphasis of the study was on application of X-ray tomography to characterize typical defects in a tetragonal polycrystalline zirconia stabilized with 3 mol% of yttria (3Y-TZP) processed by the lithography-based ceramic manufacturing. Results confirmed the practicability for non-destructive detection of typical defects in LCM processed 3Y-TZP zirconia. It also points out most defects play critical role in quality assessment and performance of these structural components. Tawfik et al. [247] used X-ray computed tomography to detect unfused powder in EBM and SLM additive manufactured components. The development of this method focused on the detection of unfused powder to evaluate the integrity of the AM components. The titanium artefact was built using an Arcam Q10 EBM machine while the aluminium artefact was built using a Renishaw AM250 SLM and AlSi10Mg powder, the powder particle sizes were 45–100 μm for titanium and 15–45 μm for aluminium. The built bars were XCT scanned with a 38.8 μm voxel size. The authors mentioned that visual inspection should be used to identify the required threshold for surface determination, whereby the exact grey value for each pixel in the defect is determined, to enhance the results by accurately detecting the material edge.

In summary, the impact of additive manufacturing cannot be overstated. Its importance across several disciplines makes it an alternative to the traditional manufacturing methods. In medicine, components such as prosthetics, trachea splints, scaffolds, implants, maxillofacial and microneedles are easier to produce and cost-effective using 3D printing. The aerospace industry has produced several high value components using 3D printing. Metallic components have been produced for Ti-based, Al-based, Cu-based, Ni-based, Co-based, and Fe-based alloys. The world has been experiencing energy crisis due to the fast depletion of fossil fuels at our current consumption rate, additive manufactured turbine blades have been a promising solution for various energy harvesting applications. In electronic devices, 3D printing has been used to fabricate components with an exceedingly small size and intricate shape much easier than the conventional methods. The building and construction industry have been able to manufacture in the areas of concrete printing, contour crafting and d-shape, by the production of excellent quality buildings and pedestrian and cyclist bridges in Spain.

5 Research output on additive manufacturing

According to the Scopus database, about 37,607 articles were published in the field of AM/3D printing between 2015 and 2021 globally. The top ten countries with the highest publications are United States (10703), China (5180), Germany (3865), United Kingdom (2803), Italy (2199), India (1842), France (1354), Australia (1189), Canada (1129), and Russia (1094). Majority of these countries are in the global North, and this has been attributed to the rich ecosystem of research and massive investment in infrastructure.

5.1 Research output on additive manufacturing research

In Africa, ~541 articles were recorded between 2015 and 2021 according to Scopus. South Africa leads the pile with about 412 published papers followed by Egypt (111), and Nigeria had 89 in third position. Countries in Africa concentrating efforts on AM/3D printing is shown in Figure 13. Most of these publications involves collaboration with institutions globally. Most of the international collaborations are from the global North, especially from United States, Italy, United Kingdom, France, Germany, Spain, and Canada. Others are from China, India, Australia, Saudi Arabia, and Brazil. This means Africa collaborates with some of the global leaders.

The first fully functional AM facility was installed in South Africa in 1994 [248–253]. However, there have been a gradual building on the foundation which is shown in the low research output between 1994 and the mid-2000s [21–25]. There has been renewed interest few years before the pandemic resulting in the general explosion in publications from 2010 to date. The high publications emanating from South Africa is due to the increased infrastructure in research councils and research-intensive universities across the country [253]. This is coupled with healthy collaboration with institutions from developed countries mostly in Asia, North America, and Europe.

According to the Scopus database, Africa is one of the least published continents in 3D printing. However, there is increasing interest due to continental and regional initiatives since the 2010s. The formation of the African

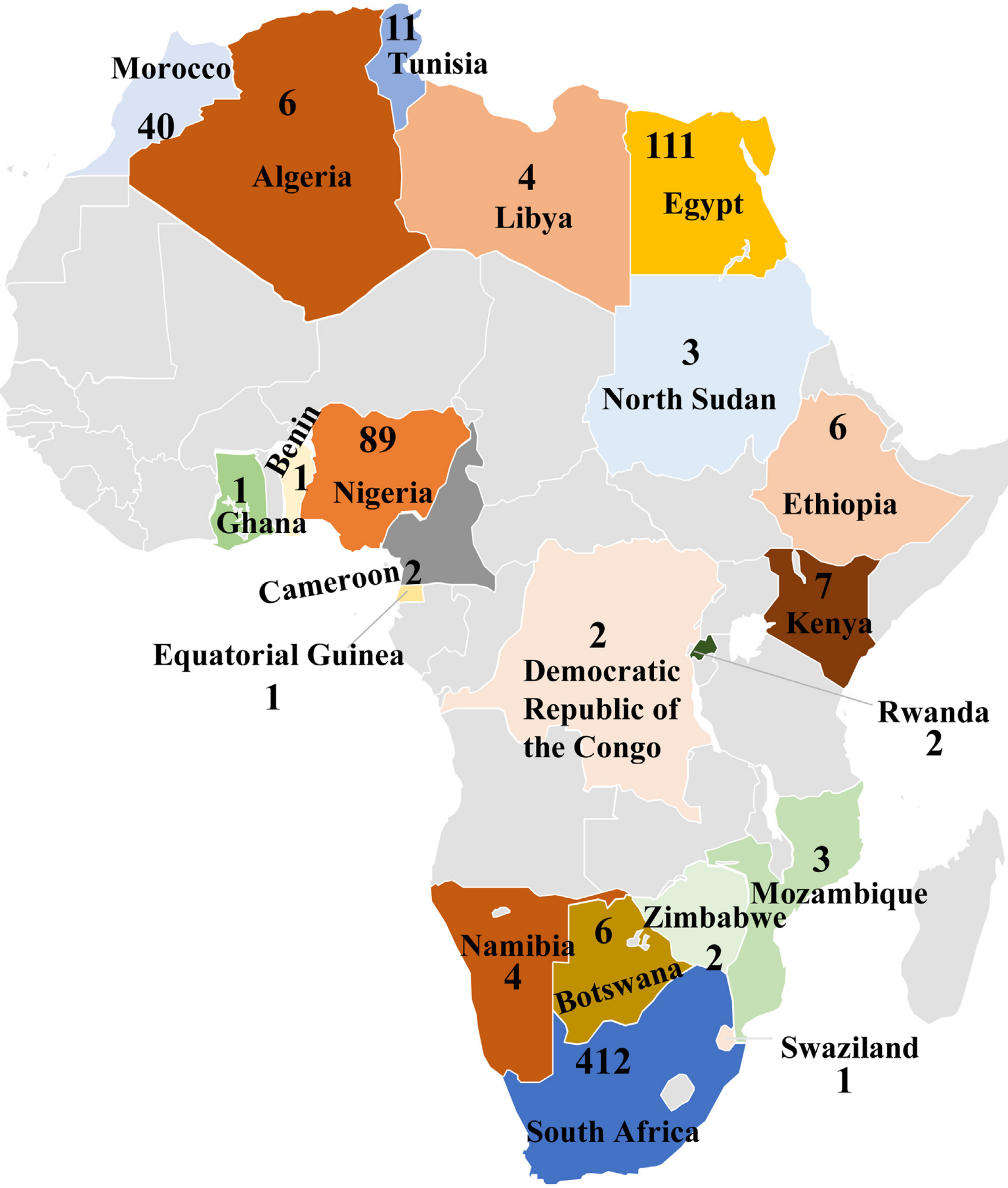

Fig. 13. Map showing AM publications in Africa between 2015 to 2021 extracted from Scopus database Classifications.

Materials Research Society (AMRS) in 2000 with funding from the United States National Science Foundation and the South African National Research Foundation was pivotal. After the biennial conferences held in 2003, several AMRS meetings were held across the continent. These were held in Morocco in 2005, Tanzania in 2007, Nigeria in 2009, Zimbabwe in 2011, Ethiopia in 2013, Ghana in 2015 and Botswana in 2017. This has boosted transdisciplinary and multidisciplinary research collaboration and cross pollination of ideas and research throughput. Similarly, there were the African Materials Science and Engineering Network program hosted in the University of Witwatersrand with partnership with countries such as Botswana, Nigeria, Namibia, and Ghana.

Africa is becoming a science and technology hub, and contributor to innovation and knowledge generation at fast pace [27–30]. This has been enforced by the formation of the Nelson Mandela Institutions, Next Einstein Forum, and the African Research University Alliances (ARUA) initiatives. The African Academy of Sciences flagship funding initiative programs for African scientists are key drivers for increasing research throughput. An example is

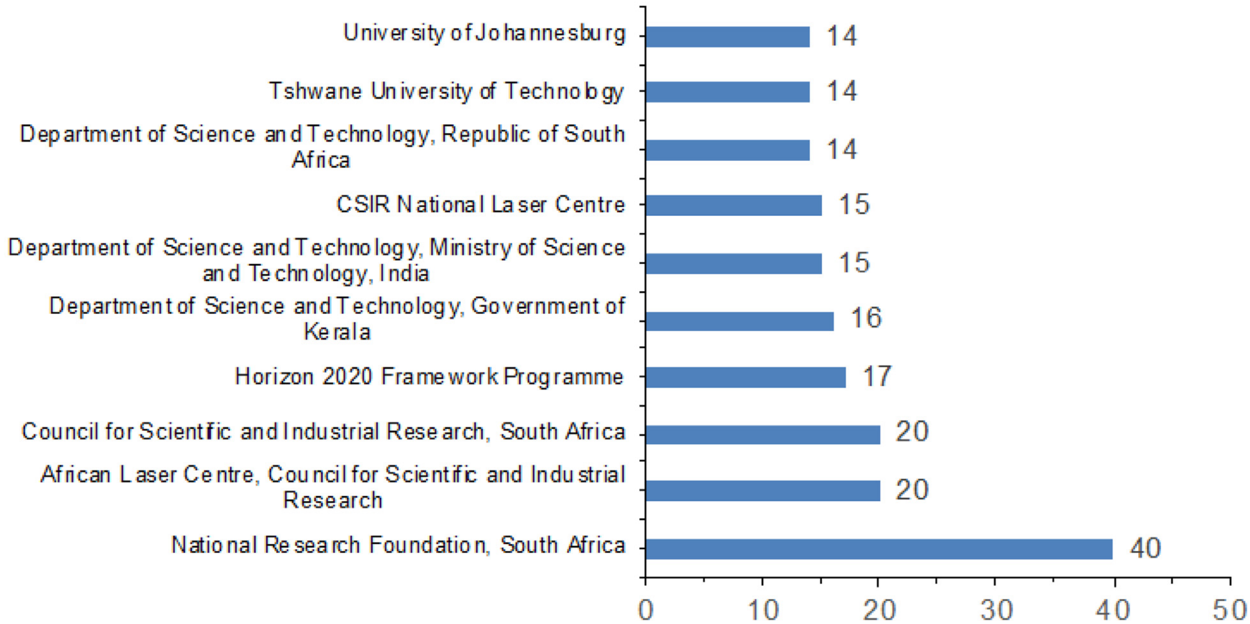

Fig. 14. Funding details of AM/3DP research in Africa (Data extracted from Scopus database).

the African Research Initiatives for Scientific Excellence Pilot Program targeting early career researchers on the continent. These programs have key research themes in areas of biotechnology, information technology and materials science and engineering, which are critical frontiers for human advancement and civilization [258]. This is coupled with strong collaboration with sister countries and those in the global north.

The South African economy boost of ~12% contribution to its GDP (Gross Domestic Product) from the manufacturing sector [253]. South Africa has a culture of funding basic and applied research as evidenced in the square kilometre array project, the colossal additive manufacturing facility at the Council for Scientific and Industrial Research (CSIR), the mineral beneficiation program at the Council for Mineral Technology (Mintek) [27–30]. Universities are strategically positioned as research-intensive with endowment funds towards research and capacity development. The top ten funding agencies for additive manufacturing work on the continent are all in South Africa, given in Figure 14. This also lay credence to the many publications emanating from South Africa [23,32]. Thus, the South African Government continues to contribute immensely to the AM/3DP research on the globe [21–25,33]. One of the main funding agencies on AM research on the African continent is the Collaborative Program in Additive Manufacturing, housed by the CSIR in South Africa. Majority of the funds are provided through various government departments such as the Science, Technology, and Innovation; Mineral Resources and Energy; and Trade and Industry.

There are three main AM/3D printing techniques widely per most of the research paper perused. These are over 109 selective laser melting, 71 fused deposition modelling and 65 direct energy deposition. These types are attributed to their low cost, portable and ease of operation [34–37]. The three techniques which have been reported in a single document include liquid deposition modelling, multi-jet fusion technology and melt electrospinning writing.

The 3D printing research throughput in Africa is mostly fundamental and experimental research. This is shown by the publications indexed in Scopus. Thus, out of the 541 publications, 59% was research papers, 26% were conference proceedings, 10% was review articles and 55 were book chapters. The principal areas of concentration are in materials science and engineering with about 200 papers, 92 were mostly on quality control, process control and quality assessment. About 85 publications focused on biomaterials, biomedical and medicine. This could be added to the materials science and engineering pile. There have been research papers highlighting the application of AM in robotics, explosives, textiles, and food.

5.2 Additive manufacturing awareness, education, and training

Africa is not big on manufacturing and depends on the rest of the world for most of the manufacturing products. The World Bank estimates ~11% of African GDP to be contribution from the manufacturing sector, which is one of its Achilles heels as minerals are not beneficiated and values added. More than 60% of spare parts and machine components in Africa are imported. Data on most African countries is rarely available. However, data from Statistics South Africa shows importation as a percentage of total manufacturing from 2010 to 2017 for the Republic of South Africa is given in Figure 15. The average distribution for that period is estimated as ~63%.

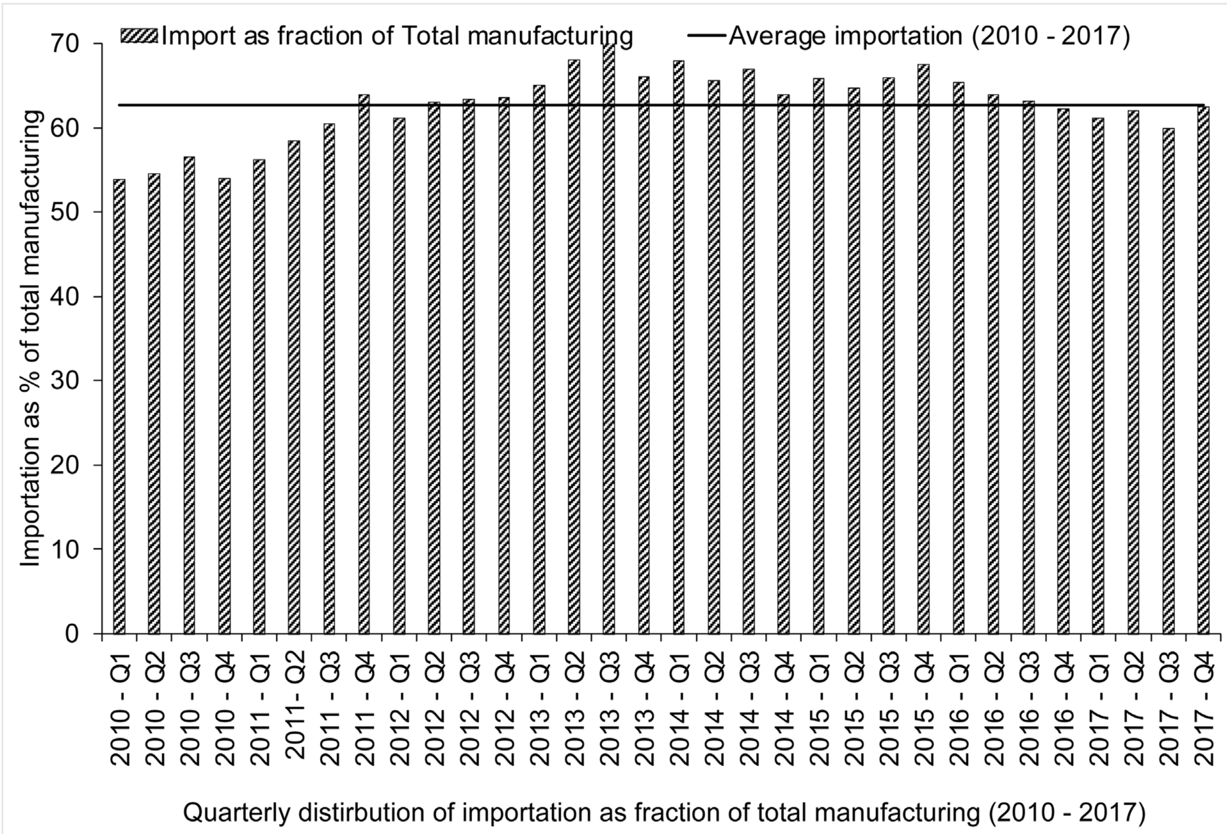

Fig. 15. Importation as a fraction of total manufacturing for the Republic of South Africa (2010–2017) (Courtesy: Statistics South Africa).

This has a direct effect on the adoption of AM technologies on the continent. The situation is further worsened by lack of policy framework and direction for the continent.

Additive manufacturing can only thrive on capacity building and robust research offerings. As an emerging field in materials science and engineering, there is the need to establish the science and then use that understanding to develop products and standard recommended practices. Thus, universities and research centres should spearhead massive curriculum development across the continent. These research centres should also be supported by local manufacturing industries for the transfer of knowledge and the technology as quick as possible. Some of the countries have developed and implemented some of these initiatives already which will be discussed briefly.

5.2.1 Additive manufacturing awareness in South Africa

South Africa has massive investment in AM facilities across the manufacturing value chain. There is an intentional and systematic infusing of AM technologies in most of the light manufacturing sector. This is backed by research from various research councils, parastatals, and institutions of higher learning. Therefore, there is a steady increase research throughput as indicated by Scopus Database. The commitment of the South African public and private sector through the establishment of the Presidential Commission of the Fourth Industrial Revolution has been a contributing factor to increased awareness for various emerging technologies.

Prior to the installation of the first fully functional AM facility in 1994, there were pockets of centres of excellence in AM research across South Africa [25,33]. These research entities and universities have increased due to increased awareness and slow transition of light manufacturing industries into smart manufacturing. One of the first was the Rapid Product Development Association of South Africa (RAPDASA) [25,33]. This organization was phenomenal in pushing for AM research and product commercialization. The RAPDASA team also forge strong international collaboration with entities such as Global Alliance of Rapid Prototyping Associations (GARPA) [25,33]. These activities are augmented by universities and research councils across South Africa [2,51,123, 219–232,263–266]. These institutions have additive manufacturing research groupings with medium to high-end 3D printers for polymers and metals. Increased research throughput is driven by the benefits of low cost implementation strategies and ease of use of AM technologies [267]. South Africa through the Department of Science and Technology in 2015 implemented the strategic roadmap for additive manufacturing [85,86]. There is concerted effort in infusing AM technologies in the conventional manufacturing landscape. This supports the high research throughput from South Africa (Fig. 13).

The rest of the African continent has much to learn from South Africa especially in areas of AM research [2,51,123,219–232,244,269,270]. The increasing funding programs through the Collaborative Program in Additive Manufacturing is commendable and a case in point. This has brought about cooperation between many research institutions and centres of higher learning to drive fundamental and applied research, resource sharing, robust scholarly engagement, cross pollination and co-creation of knowledge and products in ways that could beneficiate and add value to the mineral wealth of the continent [2,51,123,219–232,244,269,270]. This has also led to a vibrant AM ecosystem bridging the gap between the academy and industry. Some of the notable continental experts are from Stellenbosch University, Central University of Technology (CUT), Nelson Mandela University, University of Pretoria, University of the Witwatersrand and CSIR [2,51,123,219–232]. Recent advances were in the used of 3D printers of the University of the Witwatersrand for mass production of ~2500 face shields for hospitals in Gauteng Province of South Africa. Another vibrant group on AM research is Stellenbosch University Anton Du Plessis' 3D Innovation Group, which continue to make great stride with some of the industry partners as Aeroswift, Altair, LRS Implants, Executive Engineering and Rapid3D. These collaborations have extended beyond the borders of South Africa resulting in quadrupling research throughput in publications, product development and testing [2,51,123,219–232,244,268,269,270]. In the second quarter of 2021, collaborative work between Du Plessis' Group and colleagues from CUT (Igor Yadroitsev and Ina Yadroitsava), and their US counterpart Eric MacDonald from University of Texas (UT) El Paso were editors of the 658 page comprehensive reference text "Fundamentals of Laser Powder Bed Fusion of Metals [269].

By leveraging the intellectual rigor from locally and internationally acclaimed experts and state-of-the-art facilities from the "proverbial West," the South African research footprint in AM related technologies is remarkable. This active research footprint in AM technologies and the rigor associated with publications by South African researchers led to approval of the special issue in Scientific African Journal with over 90% of guest editors being local. Similarly, a new journal dubbed "Additive Manufacturing Letters," a corollary to Additive Manufacturing has emerged with most of the editors actively engaged in AM on the African continent [220]. This is a clear demonstration for sub-Saharan Africa to explore collaborative research and leverage from well-established research agencies and laboratories abroad with the technical expertise. The strong institutions in South Africa have made it possible for the continent not to lag the "Proverbial West" and to generate relevant knowledge while training homegrown scientists and engineers in ways that promote cross fertilization of ideas and resources – a linchpin for the industrialization of the continent which is within reach [252–257,258–260].

5.2.2 Additive manufacturing awareness in Egypt

Studies have been commissioned to assess the level of awareness of AM technologies in Egypt. There are two principal areas of application of AM processes in Egypt. These are in the construction and medical industry. In the construction sector, knowledge, awareness, and perceptions (KAP) study of 3D printing of ~55 participants and local designers and planners in the Egyptian market were done in 2019. The results are staggering; ~27% of participants and industry practitioners had some prior knowledge but were not fully engaged with it. About 73% had no prior knowledge which was concerning. This is a general challenge across Africa as emerging technologies and inventions at our centres of higher learning do not translate to industrial practices. There is the need to bridge the gap between academia and industry as generally observed in most problem-based curriculum in applied sciences and engineering in developed countries.

The second most published country in additive manufacturing is Egypt as shown in Figure 13. This showed there is increased research visibility and awareness of the benefits of the emerging technology. This is backed by various university, research centres and local manufacturing industries. Among these initiatives includes the Additive Manufacturing Centennial Lab in America University in Cairo focusing on wire-based additive manufacturing technology. The Egyptian National Development plan focusing on intensifying and investing in emerging technologies, i.e., additive manufacturing focusing on construction and medical devices industries. Similarly, the "PrintLab Egypt" runs the AMTech company which continues to drive AM research and product development. This has resulted in retooling and reskilling the next generation workforce in an era of overwhelming complexities, accelerated change and tremendous competition under the guise of the Fourth Industrial Revolution. Currently, 3D printers, model softwares, online courses, curriculum assessment and design are gradually being include in most formal education in Egypt. This is to position the nation to leverage from the benefits of AM and Egypt to become a global player in this arena. Some of the ancient Egyptian artefacts have been redesigned and modelled using 3D printing technologies.

5.2.3 Additive manufacturing awareness in Nigeria

There have been some initiatives in promoting AM research in Nigeria [271]. A study focusing on the level of awareness of the AM technology was conducted in South western Nigeria with over 60% of the samples having no knowledge [271]. Many of the people interviewed knew of electron beam melting, fused deposition modelling, stereolithography and laser metal deposition 3D printing types. Considering few professionals are aware of 3D printing is worrying and shows extremely low patronage in the light manufacturing sector of the Nigerian economy. A similar study focused on the perception and implementation of 3D printing in the educational sector. About 93% of engineering professionals were aware of the technologies in the educational sector [272]. While, it is encouraging for professionals to have heard of it, a deep appreciation of how the technology works is missing. This shows there is the need for the infusion of this technology in the manufacturing space and the curriculum for most undergraduate and postgraduates.

There is little private-public collaboration around 3D printing across the Nigerian manufacturing sector. For instance, the prototype engineering development institute (PEDI) and engineering materials development institute (EMDI) are set up under the National Agency for Science and Engineering Infrastructure (NASENI) to drive AM and other material related research. Currently, there are dedicated 3D printers installed for the conduct of research and sustainable AM capacity development. In 2017, Nigerian Foundries Limited purchased one of the largest 3D printing facilities from Titan Robotics. This has been used for the preparation of complex and intricate mould patterns. The full functionality is barely realized due lack of awareness and skills deficit.

Organizations like TReND organized two weeks intensive hands-on training for capacity building and awareness in 3D printing prospects in Nigeria in 2017. The 3D printing workshop was funded by Volkswagen Stiftung collaborating with some German facilitators. Similarly, another organisation called Elephab through General Electric created start-up initiative for 3D printing and prototyping of parts for various industries. It also provides skills and training programs in advanced manufacturing technologies. These trainings are not formalised through certified institutions hence few people participate. This is driven by out of interest or delegates sent from small companies or universities such facilities installed, which are hardly used or looking at exploring this good-to-have facilities.

Adopting 3D printing has faced numerous challenges in Economic Community of the West Africa States (ECOWAS), where Nigeria is one of the biggest economies. Over reliance of ECOWAS member states on importation of spare parts hindered the light manufacturing sector in the sub region [273–275]. This has stifled growth and adoption of such technologies by local manufacturers. Thus, very few established manufacturing firms can compete with these well-established importers. In most developing countries, there is little emphasis, programs, and governmental support for the manufacturing sector. Thus, there is little manufacturing being done, hence importation of machine component and spare parts are the order of the day. The dependence of Nigerian economy on spare and machine component parts importation is the main enabler of little interest in AM development. These imports are across many industries and sectors of the economy: ship building, mechanized agriculture, cement, oil refinery, railway, power generation and food processing [275].

4.2.4 Additive manufacturing awareness in Morocco

Additive manufacturing research and development has improved in Morocco. This is shown in the increasing research throughput per the publication records on Scopus (Fig. 13). This is traceable to various private-public initiatives such as the creation of the Thales industrial competence centre for metal AM research in 2016 [276], the formation of the Moroccan Association of Additive Manufacturing and 3D printing and series of International Conference on additive manufacturing, where the first was held between 19 and 20 November 2020. These conferences were aimed at providing platform for local and international researchers in various areas of AM technologies and Industry 4.0. These initiatives were in response to the 2015 industrial acceleration plan with 10 foci to accelerate industrial transformation of the Kingdom of Morocco [277].

Since its inception, Casablanca International Conference on Additive Manufacturing has concluded its second edition. Some of the areas of focus are engineering design for additive manufacturing, AM Computations, modelling and simulation, AM product development, quality control and assurance, AM applications, AM Challenges and Future prospects for Africa, Artificial Intelligence, Machine Learning, Automation and Digitalization, AM Education, training, and Research Strategy. These initiatives have public-private partnership buy-ins and supported by intensive research from centres of higher learning such as Rabat International University, Institut National des Postes et Télécommunications (INPT), Universities of Tangiers, Meknes, and Fes. AM awareness in Morocco is growing steadily but there is still room for improvement. This can be achieved by increasing collaborative partnership from the subregion and globally.

4.2.5 Additive manufacturing awareness in Tunisia

The National Engineering School of Tunis (ENIT), one of the largest engineering schools in Tunisia, introduced the first FabLab for additive manufacturing technologies and research. Regarding to design and innovation management modules, ENIT has organized seven workshops according to the "Innovation week" model, two of them were "International weeks." the FabLab was launched as in-situ students association, with students from different specialties who are responsible of running and managing the FabLab activities. More than 500 students have benefitted through training on design, innovation management and creativity. Some of the projects by FabLab include; development of a model for the calculation of prototype's cost, needs analysis for rapid prototyping in Tunisian companies, and study of the physical installation of the FabLab [278].

5.3 Applications of AM with high potential for industrialization in Africa

Africa has serious infrastructure deficit. The 3D printing technologies will be critical to delivering smart manufacturing techniques across the light manufacturing industry in Africa. Thus, construction projects will be carried out timeously and at low cost [279]. The footwear, electronic, medical devices and automotive industries in Africa can also benefit from this technology. However, a collaborative framework from all relevant stakeholders and not siloed approaches will be required for target and emerging markets.

There has been success with laboratory scaled rudimentary research and proof of concept for hybrid 3D printing in building and construction in Egypt [214]. Material grading and distribution were designed to provide a dense filler material with high water retentivity, extrudability, and flowability. Different raw materials were mixed to create a paste-like composition, which was then fabricated using the FDM process. The compressive strength of the concrete was 20 MPa. Currently, some of the process parameters are being optimised which will be compared to concretes designed using the conventional building methods. The addition of fibreglass to the concrete has also been explored contributing a 6 MPa increase to the compressive strength. Thus, material composition, apparatus design, wall design, and printing techniques for the deployment of hybrid 3DP technology in Africa is possible. This method could provide perspective on hybrid 3DP technology in Africa, especially for higher-quality and lower-cost curvilinear wall construction [224].

A capacitive 3D printed pressure sensor for educational purposes has been printed in Morocco [280]. This was fabricated due to lack of laboratory equipment for students. Currently, this technology is undergoing further testing to be certified and approved by the Moroccan government and then Africa. The main material used was the polylactic acid (PLA) using the fused deposition modelling. A conductive material was used to induce the requisite electrical conductivity. Specimens were printed in accordance with DIN EN ISO 527-2 standardization. By using the FDM 3D printing technology to create sensors in the Computer Assisted Experiment Environment (CAE), the low-cost laboratory equipment can be designed for students considering the economic woes of Africa.

Africa is a haven for most of the renewable energy resources such as solar, hydro and wind. However, energy is one of the main challenges Africa faces [281]. There is the need for innovative energy solutions which are affordable and easily accessible globally. Though about 1.6 billion people do not have access to energy, one needs to think about the financial mechanisms upon which these technologies are deployed. This is because ~3 billion people live on less than $2/day. While renewable energy is considered as the energy resources of the future, one of the main challenges is the development of the right devices. These are energy storage, electronic circuits, and elevated temperature thermal-energy application devices [112]. The conventional slurry-cast electrode technique of fabrication do not simultaneously induce high power and high energy density [112].

For a typical battery development, high power and high energy densities are desirable. The development of porous 3D electrodes and batteries using AM techniques have shown promising results. The discontinuous bulk electrodes fabricated using AM consist of active material sandwiched between high conductivity electron-transport and conductive ion pathways resulting in extremely fast charge and discharge cycle. The porous 3D electrode had better performance than conventional electrode in ways such as short ion diffusion inducing sluggish ion-transport. The electron-transport was also continuous with large surface area for electrode loading. There was an interconnected electrolyte-filled network that promote fast ion transport. A similar AM approach is used to fabricate 3D cathodes with remarkably high efficiency and capacity.

Recently, 3D-printed supercapacitors were fabricated with extremely high energy storage capabilities with long cycle life, low-cost and high-power density. Graphene-based materials were used due to high electrical conductivity, chemical stability, and large specific area [201].

Additive manufacturing has been used for the manufacturing of low-cost membranes for water treatment in some African countries. There are many water-scarce countries in Africa and globally [201]. Thus, countries below the Equator are at risk of becoming water scarce. Similarly, contamination of water is an issue, particularly in rural places where clean water is scarce. It is estimated that over 2 billion people globally do not have access to portable drinking water. To improve the situation, 3D printed membrane from clay powder and a binder solution of maltodextrin have been developed in parts of Nigeria [282]. The Kankara clay powder was taken from Nigeria. To manufacture 3D porous samples with varied mesh sizes (75, 150, 250 m), Kankara clay powder was combined with maltodextrin powders (4% concentration) as a binder fluid. Cylindrical porous samples with a diameter of 30 mm and a height of 20 mm were created. The green samples were placed in the powder bed for 2 hours after 3D printing was completed. The green samples were then removed from the job box, cleaned with an air blower, and dried in the oven for 24 hours at temperatures ranging from 40 to 100 °C and was dry. After that, the clay samples were sintered in a muffle furnace at 1300 °C for 3 hours. This was followed by compression tests with various particle sizes.

The microstructure of the as-sintered samples can be linked to the growing hardness of the surface of 3D printed components. The 3D printed clay membranes are being used as filters to remove pathogens and to purify the water for consumption, thus improving the quality of water. The use of 3D printing technology can be used to create a more efficient clay membrane. Due to the low-cost raw material and the 3D printing technique, a printed membrane is estimated to be USD $100 compared to membrane modules which is about USD $350 per square meter of membrane [282].

There have been studies initiated on 3D printed scaffolds from composite materials [133]. While this shows proof of concept, the weak interaction in the composite generates defects acting as stress concentrators with debilitating effects on mechanical behaviour. These are some of the AM studies being done by researchers in Africa. Similarly, a conceptual framework to determine the main elements influencing the AM adoption in spinal orthopaedics in South Africa was developed [283]. Key concerns of patients are good post-operative effects from a 3D-printed implant. Additive manufacturing could be a more cost-effective and fast way to offer patients with bespoke implants. Majority of surgeons interviewed attest to the benefits of AM improving the field of spinal orthopaedic surgery. This include being able to adjust the implant device for a better fit.

The top ten countries with the best output in AM/3D printing are in the global north, North America, Europe,

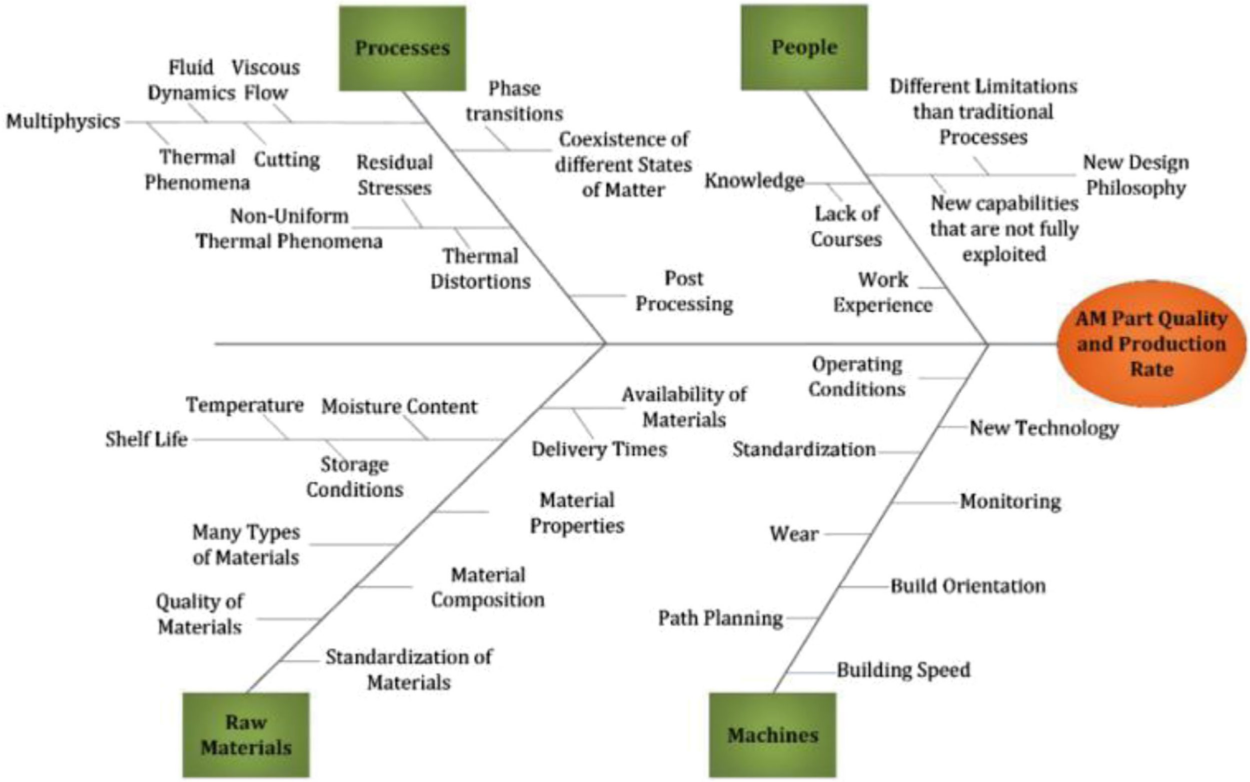

Fig. 16. Critical issues associated with AM technologies [63].

and Australia, except for China and India. South Africa leads the pile in Africa, followed by Egypt and then Nigeria. Furthermore, many publications in this field have been co-authored by international collaborators from the global north. For Africa to be able to increase its 3D printing output, it must improve in its manufacturing sector, as Africa lags in this sector. Furthermore, universities and research centres need to spearhead massive curriculum development across the continent.

6 Emerging applications and future trends for AM research

Emerging applications of AM techniques will be in current research hotspot areas. These range from low – to high – earn industries focusing on structural and functional applications, which include aerospace, semiconductor, thermoelectric, clean energy initiatives including materials for nuclear and hydrogen fuel applications. Due to the relative low wastage of materials associated with AM techniques, future trends could focus on sustainability with emphasis on scrap or "dirty alloy" metallurgy. This provides opportunities on training, investment, interoperability, market consolidation, metamorphic manufacturing, automated manufacturing ecosystems, and the fabrication of advanced materials (composites, polymers, ceramics, and advanced metals such as the complex concentrated alloys (high entropy alloys)). There is current drive for next generation structural and functional materials and the need to solve the strength-ductility trade-offs using advanced metallic alloys. While ingot metallurgy through casting has been rampant, there is increasing drive for AM processes. The versatility associated with the seven different types of AM makes it suitable to be tailored for specific engineering material. The advantages of AM over other conventional fabrication techniques are contributing factor to incremental use. This has been demonstrated in the number of intellectual property and research throughput globally. Another future trend is the transition from components to multi-material level. These are drawn from the layer-by-layer approach resulting in voxel, forming the component or product part. The layer-to-layer deposition can also result in rapid and rational design concepts of parts. Techniques such as DED, EBM and LBM have potential for modification component parts at the expense of mechanical properties.

These emerging trends are opportunities for African industrialization agenda. Africa needs to increase investment in various aspects of science, technology, engineering, arts, and mathematics (STEAM) programs. This will lead to capacity building, training, and the development of critical mass of African technocrats for value creation, spin-off companies and the democratization of knowledge generation. The African Academy of Arts and Science can provide the blueprint and masterplan, which should be filtered down to regional blocs and country specific structures. It can be argued that the inability of Africa to do quality and top-notch research in emerging areas is due to lack of funding resulting limited or no state-of-the-art facilities. However, if resources can be pulled together and drive a common research and development agenda, Africa can become the next powerhouse. Thus, the main issues that will be critical in integrating AM technologies into the African industrialization agenda should focus on people (training), processes (technical know-how), raw materials (beneficiation capabilities) and machines (tools as enablers) [63]. This is summarized in Figure 16 and opens opportunities and robust research hotspots for the world and African in particular.

The African Centre for Disease Control (Africa CDC) has demonstrated the need to consolidate resources to drive a common goal. The cooperation and resource pulling from most African countries within the on-going COVID-19 pandemic is a testament to such call. African scientists and engineers have demonstrated the quality of research, innovation and spin-off companies emanating from her shores. The latest was South African scientists being the first to sequence the "omicron variant" of the corona virus family. This is possible for hot areas such as additive manufacturing, metamorphic manufacturing and artificial intelligence, a key enabler and driver of the Fourth Industrial Revolution.

Additive manufacturing is fast growing and a driver of the technologies of the future. Thus, AM is a great unifier and the convergence of information technology, biotechnology and materials science and engineering, which are core to the industrialization agenda of Africa. As smart manufacturing is gaining traction and with the current trends of technological advancement, basic and applied research is critical in advancing the understanding and knowledge evolution of the field. Though, some perspectives on critical areas have been discussed and highlighted, areas for future research which needs attention and elucidation, especially in Africa are discussed briefly.

About 4% of all AM facilities are installed in Africa [271]. This is a cause for concern. Being a powder metallurgy base technology, investment in national and regional infrastructure would be beneficial to the mineral beneficiation strategy of most African countries. The low research throughput is testament to the lack of adequate and world class state-of-the-art facilities to drive innovative research. A massive investment in 3D printing technology will increase the research and product development footprint in Africa. The investment will also lure top notch researchers and seasoned professionals in the area to drive change. Africa will be positioned and able to add value to its mineral worth and become a global player. This will also create opportunities for job creation for the teaming youth of Africa while developing pockets of centres of excellence with global presence. It is therefore suggested that investment and revamping of AM facilities nationally and regionally across the economic blocs should increase to about 15% over a decade. This will position Africa to leverage from the gains of the Fourth Industrial Revolution which lurks.

Training and capacity building across the continent in 3D printing technologies are critical for development. When it comes to AM technologies, Africa lags the world and there are few centres of higher learning well-resourced and capacitated to run relevant undergraduate and postgraduate programs. Departments of higher educations, science and technology, trade and industries, and relevant stakeholders need to engage and draft new curriculum and upgrade some existing department to run programs in 3D printing. Currently, there are also few active research groups undertaking serious basic and applied research in AM technologies. More than two-thirds of the 55 countries do not have a dedicated department for arduous studies in the area. The continent can take a cue from the regional and pan African Institute of Material Sciences with five centres of excellence in Rwanda, South Africa, Ghana, Cameroon, and Senegal. Similar ventures will lead the transformation of Africa by applying innovative scientific thinking and training in ways that foster breakthrough discoveries. This will also invalidate the assertions held by prominent African scholars, i.e., Ali Mazrui's "African produces what it does not consume and consume what it does not produce".

Similarly, apart from few countries with national roadmap and strategies for additive manufacturing, many do not have it hence no sense of direction. This has dire consequence resulting in the missed opportunities, i.e., looming ~18% of intra and inter Africa collaboration. The deepening and increase in intra-African trade can be achieved by using various existing structures such as Africa Academy of Sciences, African Union Commission, economic regional blocs (i.e., Southern African Development Corporation, East African Cooperation, Economic Community of the West African States), African Continental Free Trade Area (AfCFTA) and centres of excellence to drive relevant research to inform policy and taking into account potential regional and continental value chains. This will ensure each country is able to leverage from each other while collectively driving the various sustainable and millennium development goals.

In the construction space, the design of functionally graded concretes which has the potential to improve material efficiency is critical. This will ensure the demerits associated with multi-material compositions for building and construction can be overcome. By using 3D printing technology, wastage of materials associated with the construction industry can be reduced by 30% as this technology focuses on near net shape design.

Portable drinking water is a major concern for most African countries. Additive manufacturing of ceramic clay membranes can be explored for water purification. This will be building on the extensive research done by Soboyejo Group at the Worcester Polytechnic Institute. Experimenting with different clay powders and binders to print clay membrane with varying tiny particle size is crucial to ensuring the entrapment of pathogens and debris during the filtration and purification process. This will improve the quality of water in most African villages and at low cost. Thus, more studies on 3DP of clay membrane for water filtration system in Africa must be conducted with emphasis on the techno-economic models. Adopting AM technologies across the continent is required to grow an export-oriented manufacturing industry, especially in a small, an open economy and free market. This is a place where research is transformed into tangible applications.

7 Summary and concluding remarks

An overview of AM technologies, classes of materials and application in various high-value low volume industries have been reviewed. Most of the industries where AM technologies are actively being used are aerospace, biomedical, energy and construction industries. An interplay of material science, machine learning and mechanistic models have also been discussed. Thus, by combining mechanistic models and experimentation, process parameters are optimised, and effects of defects associated with structural integrity investigated. The global market shares and the projections for 2025 is estimated to ~$40 billion. The top five research intensive countries in the world are United States, China, United Kingdom, Germany, and Australia. The top 25 companies that have invested heavily into AM technology and have patents to show forth were reviewed.

Africa lags the global North and has produced few articles in this area which could be due to lack of infrastructure and regional research centres and lack of critical mass of research in the area. Similarly, there is few AM applications in robotic, explosive, product life cycle, textile, and food research. Thus, there is a research niche that must be explored to promote the growth of the technologies in ways that will overhaul the conventional manufacturing technology in Africa. This article is a comprehensive document highlighting the relevant areas for Africa to leap-frog into the industrialization era and to fulfil the African Union Agenda 2063. The AM landscape is a research hotspot and Africa needs to participate fully in this area of smart manufacturing.

South Africa is the leader in AM research and application of the technology to the manufacturing sector, which contributes 11% to overall GDP. This is due to the first operational facility installed in 1994 and then supported by an ever-growing industry and government support through the creation of the centre of excellence for additive manufacturing at the Council for Scientific and Industrial Research (CSIR). The CSIR is a leader in some of the sophisticated research and product development in South Africa with local and international collaboration.

AM consciousness, education and training are particularly important to the achievement of top-level AM activities, especially in Africa. The early inclusion of AM education at the secondary and high school level will improve its level of acceptance and enhance creativity in learners of the technology at an early stage giving an opportunity for an in depth understanding. In south Africa, an encouraging level of progress has been achieved in three decades in additive manufacturing. Institutions such as National Research Foundation, African Laser Centre, CSIR and Mintek have massive investments targeted at research and development driving the innovative ecosystem of the AM technology. Similar processes are currently on-going in Egypt, Tunisia, Nigeria, and Morocco, but on a much smaller scale. Thus, other African countries are gradually following suit by dedicating or establishing additive manufacturing research laboratories in universities and research centres. However, the need for regional collaborative centres across Africa will be critical in speeding the research gains of the continent if Africa wants to become a global player. African countries can use some of the existing research centres and councils such as African Academy of Science, African Research Universities Alliance and so forth.

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