Advances In Multidisciplinary
& Scientific Research
AIMS Research Journal
A Multidisciplinary & Interdisciplinary Journal
Volume 9, No 1, March 2023 Series

Additive Manufacturing:
A Paradigm Shift for Industrialization in Africa

[1,2]**McBagonluri, F., [3,4]Klenam, D.E.P., [1]Agyepong, L., [5]Osei, E.D., [6]Mornah, D, & [7]Danyuo, Y.**
[1]Department of Mechanical Engineering, Academic City University College, Accra, Ghana
[2]Office of the Provost and President, Academic City University College, Accra, Ghana
[3]Academic Development Unit, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg South Africa
[4]School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, South Africa
[5]Department of Orthopedics Surgery, School of Clinical Medicine, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa
[6]Department of Management, College of Business. Northern Kentucky University
Highland Heights, KY USA.
[7]Department of Mechanical Engineering, Ashesi University, Berekuso, Ghana
Corresponding Author's E-mail: fred.mcbagonluri@acity.edu.gh

ABSTRACT

In this paper, the rapid evolution of a cluster of complementary technologies that have underpinned additive manufacturing is reviewed. Enabling technologies - 3D Scanning, 3D modeling, and 3D printing technologies - that have been revolutionary in bringing additive manufacturing to mainstream have also been discussed. Conventional engineering processes and its limitations are explored. Targeted applications of additive manufacturing across the depth and breadth of engineering with concrete examples: healthcare, automotive, aerospace, etc., are highlighted. The opportunities that additive manufacturing offers the nascent Africa technological landscape, and her industrialization aspirations are contextually examined and implications as such for leapfrogging as well as the opportunities for employment for its teeming youth are emphasized.

Keyword: Additive Manufacturing; 3D modelling, 3D scanning, smart manufacturing

Aims Research Journal Reference Format:
McBagonluri, F., Klenam, D.E.P., Agyepong, L., Osei, E.D., Mornah, D, & Danyuo, Y. (2022): Additive Manufacturing: A Paradigm Shift For Industrialization In Africa . Advances in Multidisciplinary and Scientific Research. Vol. 9. No. 1, Pp 1–22.
www.isteams.net/aimsjournal. dx.doi.org/10.22624/AIMS/V9N1P1

1. INTRODUCTION

Additive manufacturing is a broad term for a series of closely related technologies and their complements that forms the new paradigm in industrial manufacturing. It is the convergence of these technologies that spawned the nascent and disruptive additive manufacturing revolution. Additive manufacturing holds great potential for industrialization in sub-Saharan Africa and across the global supply chain. It provides an avenue for entrepreneurship and consequently job creation.

Recent advances in material science and engineering, especially around thermosetting and thermoplastic polymers, composites, and powder metallurgy have shown amenability to additive manufacturing processes. These advances hold great promise to the latecomers to industrialization and remain a shortcut for Africa to leapfrog into industrialization. With additive manufacturing, a decentralized workstream that ensures the convergence of distributed locations of expertise, lends itself to production of goods and services in the market of choice. Heavy investments in conventional manufacturing equipment, the requirement for in-depth technical expertise and training, and pertinent institutional controls for access to such assets are offset by additive manufacturing and its attendant protocols.

Rapid research and development in the 3D modeling, 3D design, and 3D printing sectors guarantees that aspects of conventional industries such as sculpturing, carving and pottery will soon be encapsulated by relevant additive manufacturing protocols. Africa's industries are at their most nascent state and readily amenable to taking full advantage of additive manufacturing. Additive manufacturing is a complex manufacturing process that has evolved for decades and gained significant industrial impetus in the last two decades. It offers even in its current and evolving forms significant opportunities for both conventional industries and newly evolving technology companies to improve on productivity, efficiency, and cost savings [1]. Additive manufacturing is a manufacturing process where parts are created from incrementally adding material in layers to achieve product outcomes. It is particularly useful when parts are complex, organic and/or do not amend to conventional manufacturing processes.

Additive manufacturing can print parts from powder, liquid, sheets, and metallic materials. The underlying formative process includes heat fusing, solidification, and binding. Additive manufacturing also contrasts conventional manufacturing processes that are often subtractive, implying material is systematically removed manually or using numerical control systems to achieve design objectives. The rise in additive manufacturing in the last twenty years has altered the dynamics of manufacturing through its agility, flexibility, accuracy, mass customization, and remote engagement opportunities it affords. Additive manufacturing over the last decade has evolved and relied on three equally important adjacencies to establish its domination in the manufacturing sector, namely: 3D scanning, 3D modeling, and 3D printing. This trinity of technologies has established a new paradigm in global manufacturing and it is poised to leapfrog developing nations into the global sphere of mass production. Additive manufacturing offers a democratic platform where designers and manufacturers do not necessarily have to co-locate. Additionally, industrial expertise does not have to reside within a given organization since different aspects can be outsourced and outcomes optimized.

2. OVERVIEW OF ENABLERS OF ADDITIVE MANUFACTURING

A series of evolving technologies in software engineering, IT, geometric modeling, and electro-optics, materials science and engineering converged to enable additive technologies revolution. An exploratory review of additive manufacturing is best done within the framework of the underlying technological advances that enabled it.

Conventional Modeling Systems

The industries including aerospace, medical, and construction have relied on computer-aided design software such as CATIA, PRO-E, Solidworks and AutoCAD to model parts. Digital parts have been the bane of industrialization in the last three decades. These modeling systems offer flexibility, repeatability, ease of transfer, interoperability, and real-time interaction that led to improved quality, reduce time-to-market as well as reduction in complexity. In conventional modeling, sketches, primitives and models were finalized in one of many CAD packages that were industry-specific. For instance, AutoCAD has made inroads into Construction, while CATIA for decades was the geometric modeling software of choice for the aerospace industry.

Custom Modeling Systems

The versatility that additive manufacturing offers lies in enabling technologies modeling systems until recently were not amenable to complex geometries, especially those offered by biology organs.
Beginning in the late 1990s, Geomagic led by Fung Pi [3] introduced Geomagic as a geometric modeling system with underlying mathematical models developed by Prof. Herbert Edelsbrunner [4]. This system provided the ability to transform complex scanned electronic data of organic and complex shapes into 3D models for purposes additive manufacturing processes. Materialise, a Belgium-based medical imaging and modeling software developer, was another 3D modeling software that came online in the early 2000s and was instrumental in driving changes and automation in the hearing aids industry. 3Shape is a Copenhagen-based company that works 3D data acquisition scanners and modeling of complex shapes as encountered in orthotics, orthodontal, hearing instruments, and shoe-lace. 3Shapes workflow solutions allow end-to-end operation, including the acquisition of electronic data, processing and manufacturing integrated protocols.

High Tech 3D Modeling

The integration convention of modeling processes with custom modeling have facilitated the development of complex product development. Where a geometry lends itself readily to conventional modeling sy stems Solidworks, ProE, and CATIA comes in handy. When complex anatomical structures are involved, then custom software is required for triangulation and printing. With the integration of point cloud capabilities into Solidworks, it is now possible to bring scanned point cloud data into software for triangulation and integration into conventional design workstreams. Recent advances in haptic technologies could potentially revamp the areas of geometric modeling that include virtual sculpting and painting and the transition of such products to support additive manufacturing [5]. As 3D modeling capabilities and advances occur in tandem with advances in scanning and printing technologies, additive manufacturing will continue to provide solutions hitherto impossible.

3D Scanners Technologies

3D technologies remain a viable source of data for additive manufacturing. 3D scanning technologies have evolved from proprietary technologies that initially focused on providing custom fit military uniforms to rapid prototyping for product design. Today, 3D scanners have transitioned from bulky equipment with wide fields of view to intraoral scanners for pointset data acquisition. 3D scanners come in custom product specific forms and freestyle systems that span a plethora of products. 3Shape, for instance, produces dental- and hearing-specific scanning solutions.

Artec has found application in multiple fields of human endeavors and have effectively integrated into Solidwords systems.

3D Printing Technologies

In the last three decades, additive manufacturing processes have rapidly evolved from rapid prototyping tools to manufacturing of robust parts for industrial applications. This evolution has been supported by advances in materials technologies in tandem with advances in requisite underlying electro-optics. Figure 1 [6] shows an outline of the materials inputs into the additive manufacturing processes. As indicated in Figure,1 additive manufacturing process rely on the use of thermal energy from laser or electron beams sources. This energy is directed through complex electro-optics to melt or sinter metal or plastic powder. As shown in Figure 4, other additive manufacturing processes use inkjet-type printing heads. The inkjet-type deposits a binder or solvent onto powdered ceramic or polymer that coalesces into the final part form. As shown in Figure 1, additive manufacturing derives its supporting materials sources from powder-base, solid base and liquid. Each material source is amenable to specific curing technologies.

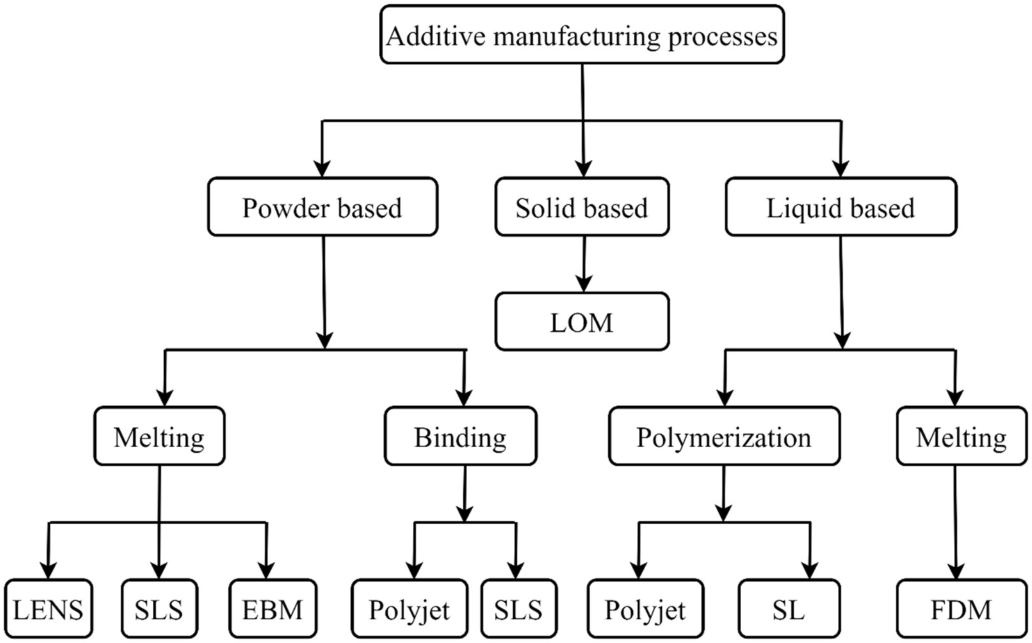


Figure 1: An Overview of the Underlying Materials Options for Additive Manufacturing Applications [6]

Fused Deposition Modeling (FDM)

Fused deposition is one of the widely used additive manufacturing processes that is relatively inexpensive. The underlying technology relies on the deposition of melted PLA, ABS or PET in the form of a filament spool. The spool of filament is pushed through a heated nozzle head in the 3D printer [7].

The extrusion head then transitions through preset coordinates and deposits material in layers that are solidified to form a part. An FDM offers product versatility in terms of color and finish; however, parts are usually brittle and hence limited in mechanical properties and applications.

Stereolithography (SL)

Stereolithography is one of the first 3D technologies to be invented. The principle behind it is vat polymerization. This process involves curing photopolymers with laser beams. The laser beams are directed by two galvanometers (galvos) positioned on the x-axis and y-axis. These galvos direct the laser beam over the resin vat, where selective curing and solidification of the product slices occur. by continuous curing layer by layer until the final part is produced [8].

Digital Light Processing (DLP)

Digital Light Processing is a 3D printing technology that is similar to SLA. Unlike SLA, however, DLP uses a digital light projector. The projector simultaneously flashes a single image of each layer. In the case of large complex parts, multiple flashes are directed at the curing material. The lights in DLP are generated from Light-Emitting Diodes (LED) or UV light. The light is directed onto the curing material by a digital micromirror device (DMD).

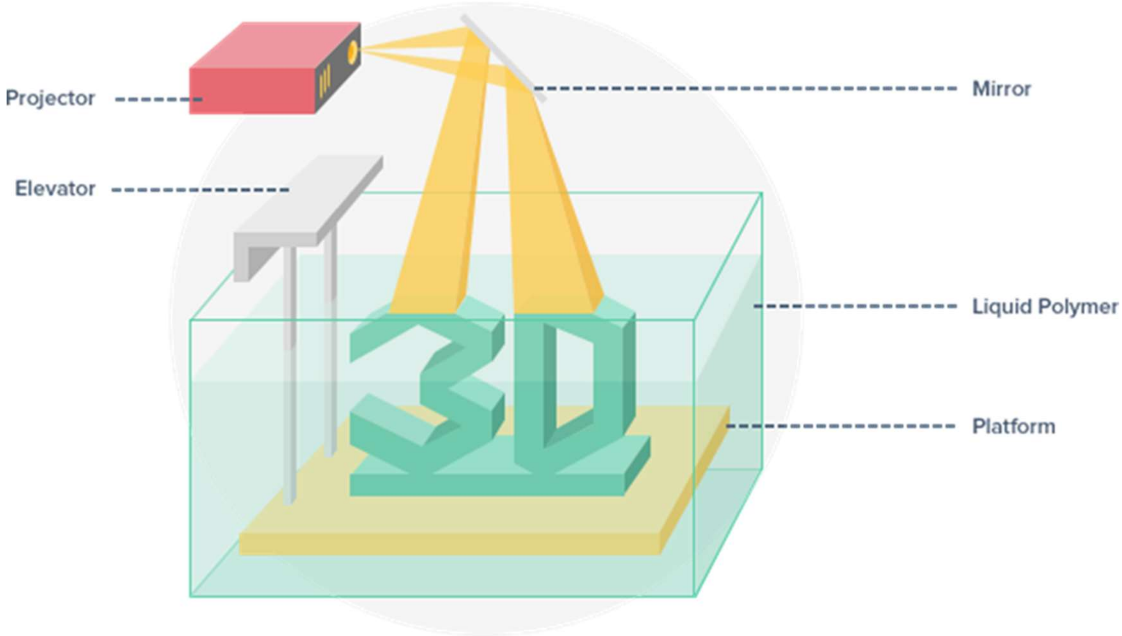


Figure 2: An overview of the DLP process
[courtesy: https://thre3d.com/how-it-works/light-photopolymerization/digital-light-processing-dlp]

The DMD is an array of micro-mirrors that are directed to generate the light structure on the build surface. This additive manufacturing process finds applications in injection molding, dental and hearing instrument systems, where fine surface finishing is required. Like SLA, DLP parts are brittle and cannot be used in durable mechanical parts [9].

Selective Laser Sintering (SLS)

As the name indicates a laser beam sinter the surface of a thermoplastic powder. The sintered power is then covered up by a wiper blade-like mechanism that spreads the powder over the previously sintered surface. The laser beam then cures the freshly spread powder. The process is repeated until the part is complete. This recoating process continues until the finished part is realized. The thermoplastic bin contains the material heated just below the melting point of the material, which is mostly nylon. This fusion process creates layered materials of about 0.1mm thick. The process also generates structures from the un-melted material around parts to support them. The SLS parts are most useful for mechanical applications. The process can output complex parts. However, the process is lengthy and expensive due low volume runs [10] [11].

Material Jetting (MJ)

This is a jet-printer for materials instead of ink. It works by firing out volleys of ink droplets to form multiple layers simultaneously rather than the layered methods associated with other additive manufacturing printing mechanisms. The droplets are cured using UV light. As a layer is deposited and cured the built platform is lowered by the equivalent layer thickness. This process is repeated until the object is formed. Material jetting is one of the fastest printing processes and is capable of simultaneously printing multiple parts and/or from multiple materials and colors [12] [13] [14].

Figure 3: a Complex Anatomical Part Made from MJ
[Courtesy https://all3dp.com/2/what-is-material-jetting-3d-printing-simply-explained]

Drop on Demand (DOD)

This additive manufacturing process is similar to the Material Jetting process. However, in the DOD process, two jets work simultaneously to create the layered structure. While one jet deposits the build-up material, the other delivers the dissolvable material. It is a point-wise deposition system that creates the cross-sectional area of the object. With this layering approach of material deposit followed by a melt, the object is constructed. DOD finds applications in medical devices and low-run injection modeling parts. Provide fine final finish, multiple material capabilities as well as color. Disadvantages Include brittleness and high costs [15].

Sand Binder Jetting

The Sand Binder Jetting process is similar to the SLS process. Parts are printed from an initial powder based on a build platform. Unlike SLS, it uses a print head rather than laser source to sinter the powder. The print head drops binder on the powder surface coalescing it layer-wise to realize the part. As the layer builds, the platform lowers for the next iteration. This process continues until the part is complete. Full color and multiple materials capabilities are supported by this process. It is used to generate mold for secondary manufacturing purposes [16].

Metal Binder Jetting

This is a binder technology similar to the sand binder jetting process, however MBJ is used principally for metal fabrication. This process requires metal powder and a polymer bind agent. To create functional parts, a secondary process such as filtration or sintering is required to enhance the mechanical properties of parts formed. MBJ can create complex geometries that are not readily amenable to manufacturing processes. During secondary processes, the binders are burning out and the resulting void are impregnated with materials such as bronze. Although known for poor mechanical properties, which can be enhanced with infiltrates, MBJ provides large volume and full color capabilities [17] [18].

Direct Metal Laser Sintering (DMLS) AND Selective Laser Melting (SLM)

These are a family of additive manufacturing processes that are similar to SLS but metal powder rather than polymer. A heat source such as laser beam is used to fuse the metal power one layer at a time. In the case of DMLS, the laser is used to heat the powder to fuse at a molecular level. SLM uses a laser source to completely melt into a monolithic part. Materials used for DMS and SLM include aluminum, stainless steel, and titanium. Parts distortion and warping resulting from high temperatures are drawbacks to this additive process [19] [20] [21].

Electron Beam Melting (EBM)

This additive manufacturing process is similar to DMLS AND SLM, however, instead of a laser energy fusion source, a high energy beam of electrons is deployed to fuse the metal powder. The energized beam melts and solidifies the powder over a cross section of the part. The repeated scanning, melting and solidifying leads to build up of the part. EBM offers better speed than DMLS and SLM.
Additionally complex geometries as well as robust functional parts can be manufactured using this process. It provides better opportunities for finer features, layers, and surface finishing. EBM drawback is the vacuum requirements and hence only electro-conductive materials can be used. These functional metal parts find application in the aerospace, automotive, medical, and dental industries. High cost and small build sizes are limitations [22] [23].

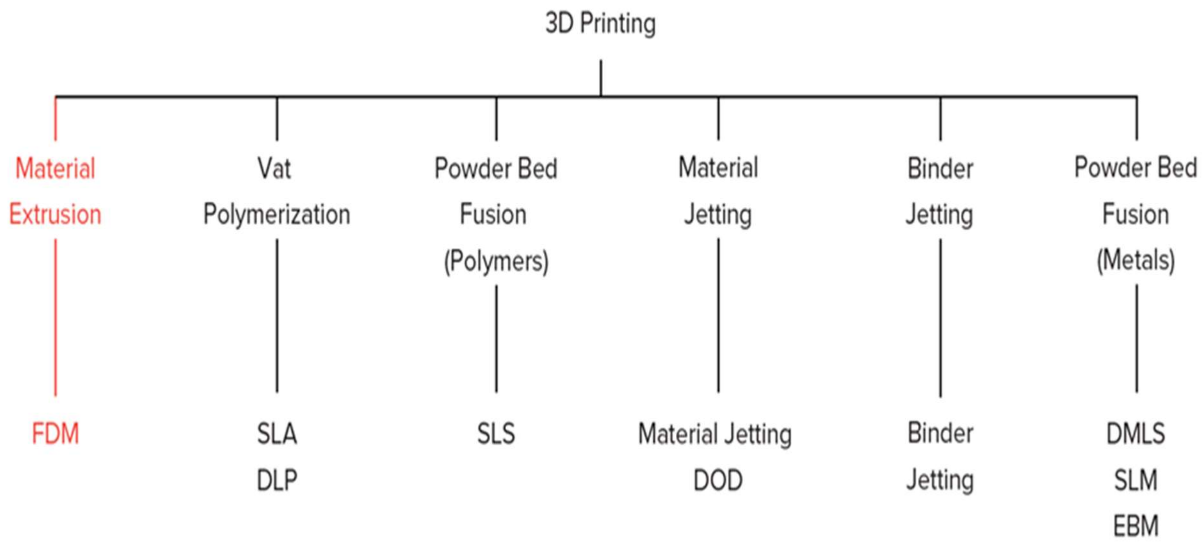


Figure 4: Overview of additive manufacturing processes
[courtesy [24]

3. EMERGING AREAS OF APPLICATION OF ADDITIVE MANUFACTURING

Medical Devices and Equipment

Additive manufacturing has shown great promise in the medical devices manufacturing space It finds applications in surgical planning, orthodontics, dental, hearing instruments and prosthetics design. The possibilities in bioprinting hold great potential for organ printing in the future as well. Siemens from the early 2000s transitioned from an intricately manual design and manufacturing of hearing instruments to using SLA and then SLS processes coupled with 3D scanning and modeling to achieve improved productivity and cost effectiveness [1].

Conventional hearing instruments manufacturing processes include taking a silicone mold of the patient and transporting it to the manufacturer via the postal system. The transported mold was then reduced to the prescribed instrument through a series of sculpturing first by a professional detailer, followed by an equally trained modeler. Instrumentation and testing subsequently followed. This process remained in place for decades with its attendant quality challenges including impression distortion during transport. This process led to pressure on manufacturing systems and consequently, backlogs up to six weeks. Additive manufacturing offered a twenty-four-hour turnaround for hearing instruments and the revolution in the industry in this regard was led by Siemens and the Sonova Groups.

This new approach relied on emerging technologies driven by 3D scanners, CATIA 3D modeling and 3D Systems to deploy hearing instruments. The scramble to automate these systems led to the development of both proprietary and custom commercial systems. Materialise, a Belgium based software and hardware company provided some of the early software for the design and additive manufacturing of hearing instruments and surgical planning modalities. It also created a 3D modeling and printing of King Tut, the Egyptian Pharaoh [25]. In the medical space, point of care of device printing for surgical planning and drug delivery has been augmented with 3D printing. Customized implants with better accuracy and reliability as well as predictive capabilities have been enabled by additive manufacturing.

Surgical guides, orthodontics, and hearing instrument molds have all transitioned from decades of technician-focused design and manufacturing to mass customization. This new revolution has resulted in decentralization of manufacturing, limited tooling and streamlined supply chain systems. Anatomical models for surgical planning and guides, educational purposes, and for transformative medical research continue to benefit from additive manufacturing. Figure 5 shows a rendered skull with customized surgical templates integrated into it. Such planning helps surgeons plan and execute complex procedures. Such templates can be additively printed for implantation [27].

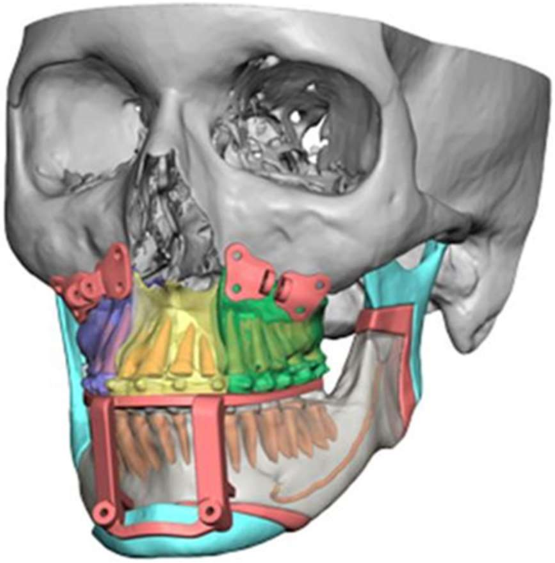


Figure 5: Surgical Guide Design Using A Haptic System
[courtesy 3dsystems].

In the medical devices arena, additive manufacturing has facilitated efficiency gains, quality improvements, and complex product manufacturing. It has also solved returns and rejection rates, a sore point in customer satisfaction in the hearing instruments industry, for several decades. In fact, additive manufacturing used in conjunction with advanced measurement has enabled the design and development of products that were previously impossible to make.

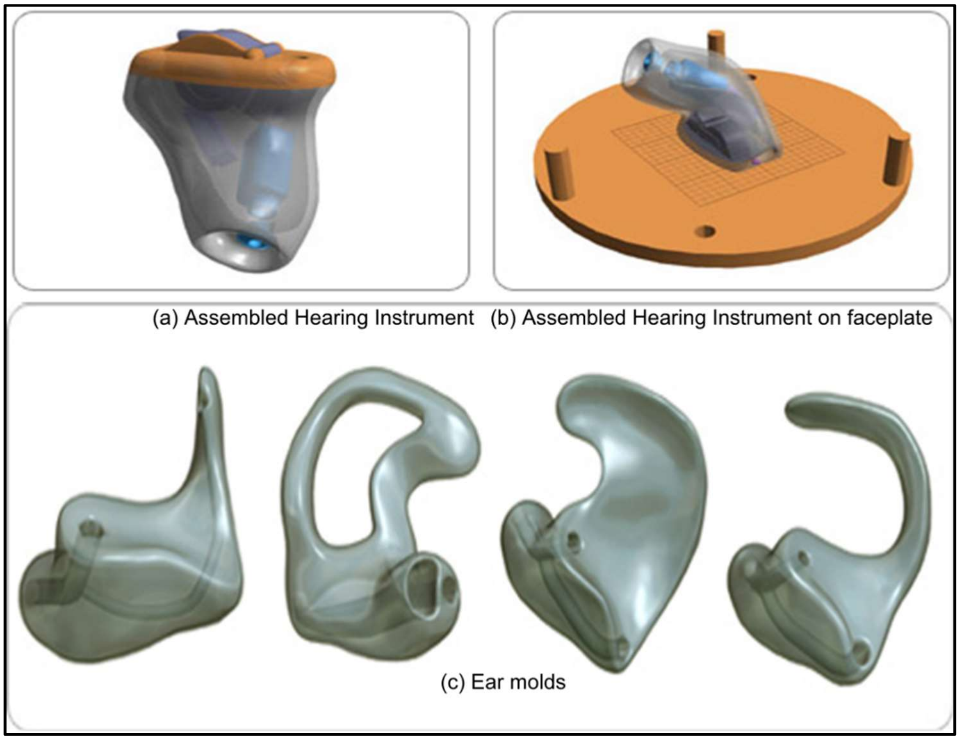
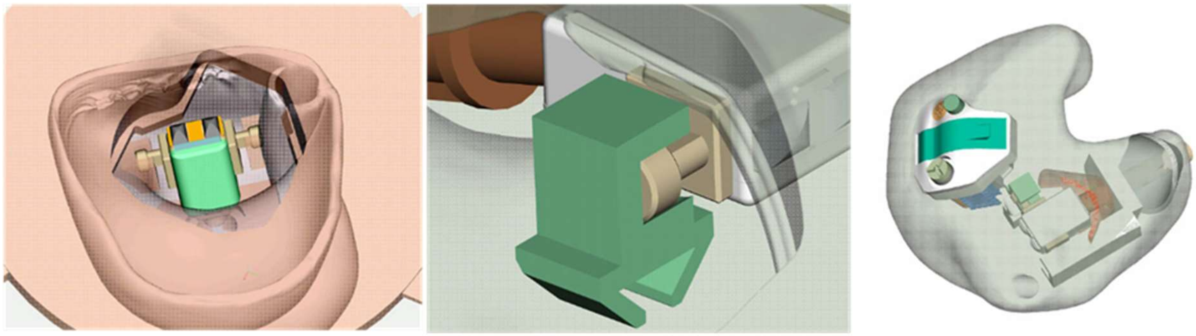


Figure 6: Hearing Instrument (Top) and Ear Molds (Courtesy 3Shape)

Figure 6(a) and (b)shows a hearing instrument assembled and an electronic mounted faceplate from which the complete assemble is achieved. Figure 6(c) shows a hearing mold made from acrylic that is used in situations of pediatric hearing fit or for profound hearing losses that require a behind-the-ear instrumentation.

Figure 7 shows a cluster of in-the-ear hearing instruments all modeled in proprietary 3D modeling software configured for hearing instruments design and manufactured using 3D system SLS.
Figure 8 shows an optimized hearing instrument system designed by electronically compartmentalizing the interior of the shell prior to additive manufacturing. The completed shell with the compartments then facilitates the placement of physical electronics components in assigned locations. This ensures optimization of component placement as well as improving speed of assembling. The ability to develop these interior compartments reduce time-to-assembly and consequently turnaround times. Additionally, shell size optimization, robustness, and shell integrity are guaranteed [28], [29], [30].

Figure 7: Clusters of hearing Instrument created with SLS additive manufacturing systems
(Courtesy Siemens Hearing Instruments).



(a) Receiver suspension (b) Side view Receiver suspension (c) Cased Receiver suspension

Figure 8: Optimization of receiver assembly based on individual shape of ear canals (a) Green receiver suspended in an apartment inside shell (b) a special structure printed in shell to support receiver (c) a final placement of receiver with virtual assembly of faceplate.
(Courtesy Siemens)

Footwear Manufacturing and Orthotics

In the footwear industry, additive manufacturing has gained significant impetus in the design of footwear. The use of advanced measurement systems facilitates the underlying orthotics that inform show design and its performance. 3D laces prototype has been designed by Adidas shoe manufacturing for decades before additive manufacturing gained global attention.

The shoe industry is transitioning from using additive manufacturing as a rapid prototyping tool. The trend is towards a holistic design that includes engineered performance and customization. Figure 9 shows a shoe last design that previous was manufacturing sculpted from wood. Now these can be obtained from scanned preforms or design using conventional modeling methods and additively manufactured. The requirements for improved performance, comfort, and agility will continue to require knowledge-drive foot design technologies and modalities.

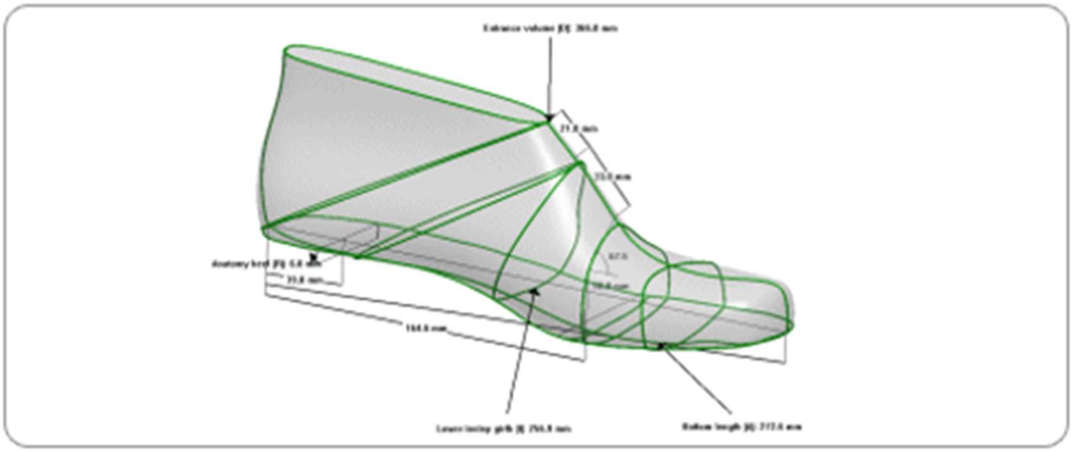


Figure 9: Shows a 3Shape shoe last [Courtesy 3shape]

Aerospace and Automotive Engineering

GE has been a pioneer in the use of 3D additive manufacturing (AM) processes including a record of producing the first fully miniaturized jet. The GE 90 was the first plane to take flight with a 3D printed engine component. The part was created from Cobalt-Chromium alloy and could operate at temperatures more than 1,800° F [31]. Additive manufacturing offers the aerospace industry the opportunity to design and manufacture components and structures, which cannot be achieved with conventional manufacturing processes. In an industry that requires products' functional excellence, an interplay between strength and toughness, decreased weight, and lower costs, advances in metal additive manufacturing have been the light at the end of the tunnel [32]. Figure 10 shows a light aerospace bracket printed using additive manufacturing.

Figure 10: A light weight aerospace bracket additively printed
(Courtesy 3D Systems).

Figure 11 shows a production of propulsion system components with freeform fluid channel designs. This design was configured to reduce turbulence, eliminate, or diminish pressure fluctuations, be light in weight, and account for stringent space requirements.

Figure 11: Fluid Management system (Courtesy 3D Systems) [32]

Electro-Mechanical Systems

Recent advances in 3D metal printing is shifting manufacturing paradigm and opening up new design in areas such as electro-mechanical systems. The manufacturing Technology Center (MTC) in the UK has initiated a project to integrate additive manufacturing processes into its design of electric motors [Figure 12]. The focus includes the redesign of the motor casing by providing liquid-cooling channels to reduce overheating, reduction of overall product weight up to 10% and size optimization of 30% [33].

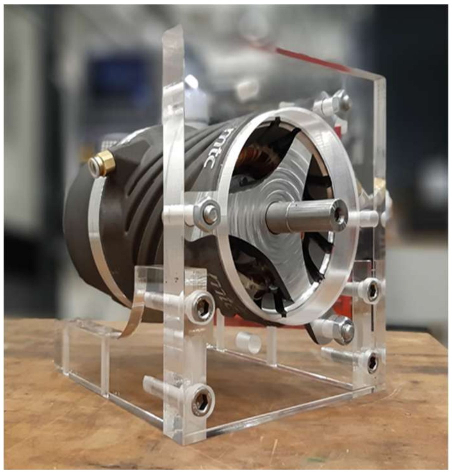


Figure 12: A redesign electric motor with cooling channels to reduce overheating and weight reduction (Courtesy MTC, UK)

4. CURRENT INDUSTRIALIZATION LANDSCAPE IN SUB-SAHARAN AFRICA

The industrial landscape in Sub Saharan Africa is blighted. Except for South Africa, most sub-Saharan African countries lost their initial industries that preceded independence. Major industries in steelworks, glass, tyre, radio, cannery, are blighted by political instability, corruption-driven procurement practices, and the structural adjustment program instituted by the Brentwood Institutions. Sub-Saharan economies have relied on the export of mineral extractions, petroleum, and natural gas products. Additionally, these countries have relied on foreign loans and grants to augment their economies. The challenges are further exacerbated by the proliferation of cheap Chinese goods and the dumping of environmentally unfriendly electro-mechanical waste in the forms of second clothes and machinery. These prevailing conditions have stifled opportunities for organic development of local industries. Additive manufacturing offers potential to cross this chasm.

Additive manufacturing – concepts and prospects for global economy

Additive manufacturing has come a long way. It has transitioned from a rapid prototyping tool to a tool for design consumer products and finally as an integral part of advanced manufacturing. Additive manufacturing has established itself as an integral part of the global economy. Events such as the pandemic will only enhance this transition. Footwear industries led by Adidas in the early 2000s adapted additive manufacturing for making prototypes for shoe last. GE aircraft has initiated process for manufacturing engine blades from additive manufacturing. Mass customization of hearing instruments by the leading hearing aid companies (Siemens and Sonova Groups) transitioned to using additive processes over two decades ago. Surgical planning, custom orthopedic implants, face reconstruction, dental implants and reconstruction have all benefited from additive manufacturing. Companies such 3Shape (www.3hape.com), Materialise (www.Materialise.be), Geomagic (www.geomagic.com), 3D systems and Solidworks have all been at the forefront of providing adjacent technologies to augment the drive towards the additive manufacturing revolution.

Additive manufacturing in response to Covid-19

Additive manufacturing proved its worth as covid-19 pandemic devastated established global supply chains. The need for PPEs and the inability to meet global supplies as factories configured for the decades without the benefits of looming disasters were now faced with the act of the impossible.

Face masks, shields, and PPE essential all parts of covid-19 prevention and barriers to cross infestation were produced *en masse* using open-source design distributed across the internet. The availability of opened sources 3D models online and ability to initiate remote local production has given significant validity to additive manufacturing and the potential that it holds for some of the most under-developed economies to jumpstart industrialization.

Additive manufacturing paradigm in Sub-Saharan Africa

Additive manufacturing offers Africa, especially sub-Saharan Africa, an industrialization of lifeline and a wand. These offers are multifold and include among others rapid production of products already developed elsewhere for local mass production. Such products could include spare parts of hard-to-find industrial equipment and machinery as well as for the booming and often old car industries here. Major construction companies often abandon heavy equipment in the field due to inability to readily access parts and components.

These abandoned vehicles are usually subjected to scrap harvesting by unscrupulous people taking advantage of the lull between finding and shipping parts from abroad or when such vehicles begin to indicate decade. Start-up companies in Africa could find opportunities in the scanning and archiving of vehicular components, printing of new houses or to vertically integrate a business across the span of scanning, modeling, and printing and essentially augmenting the current spare parts supply chain in Africa. Another major thrust for additive manufacturing in Africa could be in the medical devices and equipment space. The design of prosthetics for the handicap and custom-fit implants for hip replacement is a major area of investment opportunity in sub-Saharan Africa, where such operations are only associated with the elite, who can have sure procedures completed abroad. Basic splints to address dislocations, customized or otherwise, is an area of interest for additive manufacturing.

The leisure industries for children especially lends itself readily to additive manufacturing. Tons of Chinese produced toys inundate the opened markets of the African landscape. Most of these trinkets are imports that arrive in many containers crisscrossing the continent. Most of these toys can be mass produced locally sparing congestion in the ports and providing opportunities for local employment. Education in Africa remains theoretical. An investment in 3D printed teaching materials in the forms of anatomic parts, simple physics experiment setup and demonstration model of geometric parts could be essential in addressing chronic issues associated with delivery quality of education in response to the SDGs.

The Dutch company, MX3D recently opened a 3D printed pedestrian bridge in Amsterdam. This project was led by a team from Imperial College London. Sporadic floods in Africa render many roads useless [34]. Rapid reconstruction and construction offered by additive manufacturing could provide opportunities for just-in-time replacement bridges. These bridges could be topologically and structurally adapted to prevent dislodging. Such designs also offer the opportunities to remotely monitor structural integrity, damage tolerance, and durability. These variables could provide insights on inspection cycles, preventing the prevailing disastrous outcomes seen during periods of torrential rains.

3D construction technologies present opportunities to rapidly build new communities. Housing deficits in the developing world could present opportunities to rethink the homes of the future. A recent 3D construction of a school in Salima, central Malawi in just 15 hours provided an avenue for effective education. The deficit in school infrastructure and the dire need to educate a teeming population of 18-year continent-wide average age will benefit from the feasibility, speed, and practicality of such constructions [35].

Figure 13: A 3D printed school building in Malawi [Courtesy World Economic Forum]

Japanese scientists at Osaka University [36] recently presented a 3D printed Wagyu beef [see Figure 14]. This is essentially a bioprinting process that offers opportunities to create foods-of-the future. Bioprinting food sources could augment genetically engineered food products of the future to sustain a teeming world population.

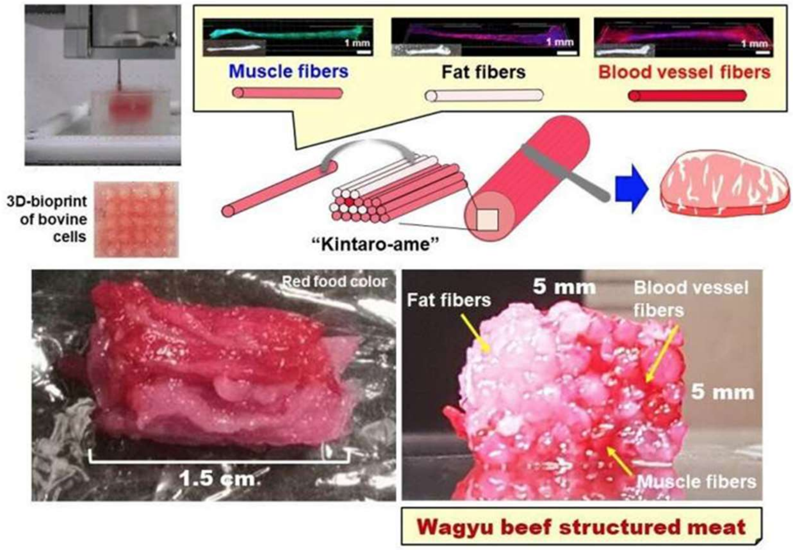


Figure 14: An overview of the Waygu bioprinting process [Courtesy University of Osaka]

From the foregoing, it is evident that sub-Saharan Africa will find core developmental challenges addressed by the rapidly evolving opportunities that additive manufacturing holds. Additive manufacturing technologies are unbounded and unlimited. Areas of potential applications to resolve intractable problems are in construction, education, healthcare, space exploration..

5. CHALLENGES AND DIRECTIONS FOR FURTHER RESEARCH IN SUB-SAHARAN AFRICA

Additive manufacturing research in sub-Saharan Africa should be centered around two loci: Materials Science and Engineering and Electro-optics. Sub-Saharan Africa is an evolving built environment with a potentially teeming population. The ability to construct low-cost housing projects relying on local materials and additive manufacturing technologies could be essential in solving the projected housing deficit. Buildings generated from local clay, tall-grass, and binder materials would result in readily deployed printable houses that take into consideration the climatic, geomatic, and geologic elements of the sub-Saharan Africa terrain. Research around materials whether as matrix, reinforcement, or composites are essential in broadening the range of application for additive manufacturing.

Combination of materials and new evolving areas in additive manufacturing could lead to the development of intelligent materials for infrastructure applications [37]. Other opportunities could include the ability to print bio-inspired materials systems for use in disaster prone areas. These could take the forms of integrated waste-plastic converted into floatable construction materials or high shear resistant construction materials that can avert dynamic shear associated with seismic activities [37]. Research on the electro-optics side could look at how advanced technologies could be developed or existing once reconfigured to construct products quite common in the sub-Saharan Africa region. In the medical devices space microfluidic devices could be printed to perform multiple laboratory functions in diagnostics [6]. Such mass production could reduce costs and grant access to many people.

Access to clean water remains a major challenge in many parts of sub-Saharan Africa. Technologies that allow low-cost water filters to be additively printed will facilitate access and reduce water-borne mortalities in these places. The efficiency gains that additive manufacturing offers and its ability to support a decentralized product design, development and manufacturing protocols lies in its underlying Information technology infrastructure. Information Technology infrastructure remains an enabler of additive manufacturing. The ability to transfer files, the design and development of product specific modeling software systems, the complex products requirements engineering, and software architecture are all explicit requirements for a functional and integrated additive manufacturing protocol.

Figure 15 shows a conceptualized Venn diagram of the underlying infrastructure to support an efficient additive manufacturing process. An integrated additive manufacturing has at its core the design tools or the reverse engineering systems supported by the scanners, modeling software and the rapid manufacturing technology.

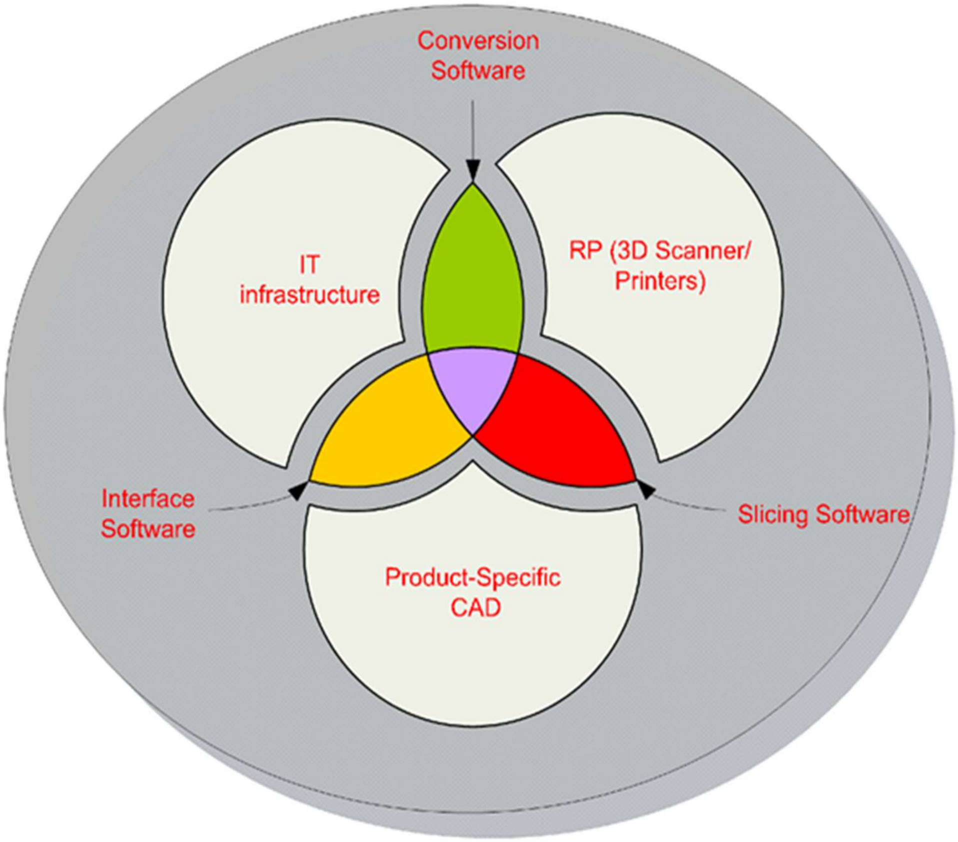


Figure 15: A Framework for enabling Additive Manufacturing is its dependencies [5]

Central to this, is the IT infrastructure and myriad enabling software technologies that facilitate the additive manufacturing process. Peripheral software that include data translation and slicing or embedded software systems that facilitate firmware performance. The IT infrastructure underpinning additive manufacturing include the manufacturing execution software systems, logistics software systems, product programming and software systems that drive the overall integration and efficiency gains.

6. CONCLUSION

The Africa terrain is ripe for industrialization. With a teeming youth population poised to access western technological advancements and the desire to alleviate unemployment the options for development are few. Political agitation and social polarization could be the outcomes if governments in the subregion miss the opportunities that industrialization holds for the betterment of the youthful population. While African perhaps has missed the first three industrial revolutions, the fourth appears to hold multiple promises and additive manufacturing offers a tangible and sustainable growth path forward.

One of these promises is the possibilities that additive manufacturing holds in helping to leapfrog to full-blown industrialization. Like the introduction of cellphones that essentially broke the stifling barriers of home phone acquisition, outdated internet cafes and democratized access to information even in the remotest parts of Africa, additive manufacturing is similarly poised to offset the dynamics and consequently the balance of power.

Time-to-market for African innovation could be enhanced by the prospects offered by rapid prototyping. Automotive spare parts, an essential commodity in Africa with demand aggravated by non-existent and gorged highway networks could be locally manufactured. The long and grueling waiting from supply chains for products being shipped from Europe and China could be alleviated by additively manufacturing components and systems locally. Medical equipment in the forms of prosthetics, hearing instruments, dental surgical gages and many more such products could be designed locally or outside and manufactured locally. Africa offers multiple sources of materials that could be inputs to additive manufacturing. The processing of these materials to support additive manufacturing could be sources of employment for many. The strategic alignment of the underlying policies in research and development to support such transition will be in the best interest of the political elites and leadership.

REFERENCES

1. Rapid Manufacturing: An Industrial Revolution for the Digital Age. Ed. Hopkinson, N., Hague, R. J. M., and Dickens, P. M. Wiley, London: 2006.
2. Master, M, Therese V., and McBagonluri, F. *Rapid Manufacturing in the Hearing Industry*. In Rapid Manufacturing: An Industrial Revolution for the Digital Age. Ed. Hopkinson, N., Hague, R. J. M., and Dickens, P. M. Wiley, London: 2006.
3. *Lauren K. Ohnesorge (3 January 2013).* "Geomagic's Ping Fu sells her company to S.C. partner". Triangle Business Journal. Retrieved 19 March 2013.
4. Edelsbrunner, Herbert. Geometry and topology for mesh generation Cambridge Univ Press: 2001.
5. http://www.sensable.com/products-claytools-system.htm
6. Wong, Kaufui V. "A review of additive manufacturing." *ISRN Mechanical Engineering* 2012.
7. Fused Deposition Modeling Based 3D Printing (Materials Forming, Machining and Tribology) 1st ed. 2021 Edition by Harshit K. Dave (Editor), J. Paulo Davim (Editor)
8. Stereolithography. Ed. Bartolo, P. J. Springer; 2011th edition (April 6, 2011)
9. https://thre3d.com/how-it-works/light-photopolymerization/digital-light-processing-dlp.
10. Kumar, S. Selective laser sintering: A qualitative and objective approach. *JOM* 55, 43–47 (2003).
11. M.M. Sun and J.J. Beaman, "A Three-Dimensional Model for Selective Laser Sintering," Proceedings of Solid Freeform Fabrication Symposium, vol. 2 (Austin, Texas: University of Texas at Austin, 1991), pp. 102–109.
12. Hongyi Yang, Jingying Charlotte Lim, Yuchan Liu, Xiaoying Qi, Yee Ling Yap, Vishwesh Dikshit, Wai Yee Yeong & Jun Wei (2017) Performance evaluation of ProJet multi-material jetting 3D printer, Virtual and Physical Prototyping, 12:1, 95-103, DOI: 10.1080/17452759.2016.1242915.
13. Yuan J, Chen C, Yao D, Chen G. 3D Printing of Oil Paintings Based on Material Jetting and Its Reduction of Staircase Effect. *Polymers*. 2020; 12(11):2536.
14. Jabari, Elahe et al. "High Speed 3D Material-Jetting Additive Manufacturing of Viscous Graphene-Based Ink with High Electrical Conductivity." Additive Manufacturing 35 (2020).
15. Jo, B.W., Lee, A., Ahn, K.H. et al. Evaluation of jet performance in drop-on-demand (DOD) inkjet printing. Korean J. Chem. Eng. 26, 339–348 (2009). https://doi.org/10.1007/s11814-009-0057-2
16. Le Néel, T.A., Mognol, P. and Hascoët, J.-Y. (2018), "A review on additive manufacturing of sand molds by binder jetting and selective laser sintering", *Rapid Prototyping Journal*, Vol. 24 No. 8, pp. 1325-1336. https://doi.org/10.1108/RPJ-10-2016-0161
17. Li, M., Du, W., Elwany, A., Pei, Z., and Ma, C. (June 25, 2020). "Metal Binder Jetting Additive Manufacturing: A Literature Review." ASME. *J. Manuf. Sci. Eng*. September 2020; 142(9): 090801. https://doi.org/10.1115/1.4047430
18. Frazier, W. E., 2014, "Metal Additive Manufacturing: A Review," *J. Mater. Eng. Perform.*, 23(6), pp. 1917–1928.

19. Yap, C. Y., Chua, C. K., Dong, Z. L., Liu, Z. H., Zhang, D. Q., Loh, L. E., and Sing, S. L., 2015, “Review of Selective Laser Melting: Materials and Applications,” *Appl. Phys. Rev.*, 2(4).
20. Li, M., Du, W., Elwany, A., Pei, Z., and Ma, C., 2018, “Binder Jetting Additive Manufacturing of Metals: A Literature Review,” ASME 2019 International Manufacturing Science and Engineering Conference, College Station, TX, June 18–22, p. V001T001A033.
21. Olakanmi, E. O., Cochrane, R. F., and Dalgarno, K. W., 2015, “A Review on Selective Laser Sintering/Melting (SLS/SLM) of Aluminium Alloy Powders: Processing, Microstructure, and Properties,” Prog. Mater. Sci., 74, pp. 401–477. 10.1016/j.pmatsci.2015.03.002.
22. Murr, L. E., 2015, “Metallurgy of Additive Manufacturing: Examples From Electron Beam Melting,” Addit. Manuf., 5, pp. 40–53. 10.1016/j.addma.2014.12.002.
23. Murr, L. E., Gaytan, S. M., Ramirez, D. A., Martinez, E., Hernandez, J., Amato, K. N., Shindo, P. W., Medina, F. R., and Wicker, R. B., 2012, “Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies,” J. Mater. Sci. Technol., 28(1), pp. 1–14. 10.1016/S1005-0302(12)60016-4.
24. https://www.hubs.com/knowledge-base/introduction-fdm-3d-printing]
25. (https://www.fabbaloo.com/2010/06/materialise-replicates-king-tut-html).
26. *https://www.3dsystems.com/healthcare/craniomaxillofacial-solutions?ind=medical*
27. Lauren K. Ohnesorge (3 January 2013). "Geomagic's Ping Fu sells her company to S.C. partner". Triangle Business Journal. Retrieved 19 March 2013.
28. Saltykov, O and McBagonluri, F. Hearing aid receiver with vibration compensation US Patent 8, 160, 283, April 17th, 2012.
29. Saltykov, O and McBagonluri, F. Hearing Aid with enhanced vent US Patent 8,265,316.
30. McBagonluri, F., Saltykov, O., Salman, P. Feature protection for stereo lithographic manufacturing processes. US 8, 077,894 December 13, 2011.
31. (https://www.ge.com/news/reports/5-ways-ge-changing-world-3d-printing?gclid=CjwKCAjw1JeJBhB9EiwAV612yxWCJPLtRMgbMsBodJoVZQDZMPcIV_UQ7PzKvF6SLHRDRqp_l2kMshoC2iMQAvD_BwE).
32. https://www.3dsystems.com/aerospace-defense/lightweight-brackets?ind=aerospac
33. (https://www.the-mtc.org/media/uy0j4m4t/mtc_case_study_-_additive_manufactured_electric_motor.pdf).
34. (https://www.popularmechanics.com/technology/infrastructure/a37246918/worlds-first-3d-printed-steel-bridge/?utm_source=reddit.com).
35. https://www.weforum.org/agenda/2021/07/could-3d-printed-schools-be-transformative-for-education-in-africa/
36. https://phys.org/news/2021-08-3d-bioprinted-wagyu-beef-like-meat.html
37. Allamed, Seyed. On the Development of a 3D Printer for Combinatorial Structural Composite Research. ASME 2015 International Mechanical Engineering Congress and Exposition. November 13–19, 2015 Houston, Texas, USA.

38. McBagonluri, Fred, Raj Varadarajan and Tong Fang. (2009). Applications of Advanced Imaging Technologies in the Customization and Optimization of Medical Devices. SME Conference Schaumburg, Ill 12-15th May 2009.
39. Allamed, Seyed. On the Development of a 3D Printer for Combinatorial Structural Composite Research.ASME 2015 International Mechanical Engineering Congress and Exposition. November 13–19, 2015. Houston, Texas, USA
40. Chaowei Wang, Zhijiang Hu, Liang Yang, Chenchu Zhang, Leran Zhang, Shengyun Ji, Liqun Xu, Jiawen Li, Yanlei Hu, Dong Wu, Jiaru Chu, and Koji Sugioka. Magnetically driven rotary microfilter fabricated by two-photon polymerization for multimode filtering of particles. Optics Letters. Vol. 46, Issue 12, pp. 2968-2971 (2021).