International Journal of Applied Engineering Research ISSN 0973-4562 Volume 14, Number 1 (2019) pp. 296-303

The Recent Systematic Approaches of 3D Printing Technologies

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Abstract

3D Printing or Additive Manufacturing (AM) is well known for its waste reduction, customization and ability to develop complicated structures. Rapid prototyping technologies play a vital role in the manufacturing of prototypes or products, that is efficient from many traditional manufacturing techniques, it uses Computer-Aided Designs (CAD) to convert it into a physical prototype with utmost accuracy and reducing the lead time. A comprehensive review of major AM techniques and corresponding development in latest applications was carried out. In addition, the paper talks about the processing challenges, limitations in layer-by-layer appearance and computer design. Overall, the paper provides an overview of AM technologies, along with the advantages and disadvantages of the benchmark for future research and development.

1. INTRODUCTION

3D printing is a technique for prototyping a wide range of complex geometries and structures from the 3D model data, the model is designed using the aid of a computer (CAD) but the additive manufacturing machine does not accept the design language so the computer-aided design format is converted in Standard Triangular Language (STL) format. The modified file format contains the dimensional and coordinate data. The STL program slices the model in several layers of different thickness varying from (0.01 to 0.7) mm, which depends upon the technique, utilized to prototype the design. Charles Hull has developed this technology in 1986 in a process known as stereolithography (SLA), which was followed by subsequent developments such as, fused deposition modeling (FDM), powder bed fusion, contour crafting (CC) and inkjet printing. Rapid prototyping has been widely applied in different industries, including aerospace, construction and biomechanical. Since, there is an advent need for product customization in these industries, which has been a struggle for manufacturers due to the high cost of manufacturing tailored fit prototypes for end users. These customized products can be 3D printed with substantially lower prices. Fig.1 Shows the flow chart of general manufacturing process.

As assessed by Wohlers Associates, customized practical items are by and by turning into the pattern in 3D printing. They anticipated that around half of 3D printing will circle close to the generation of business items by 2020 [1].

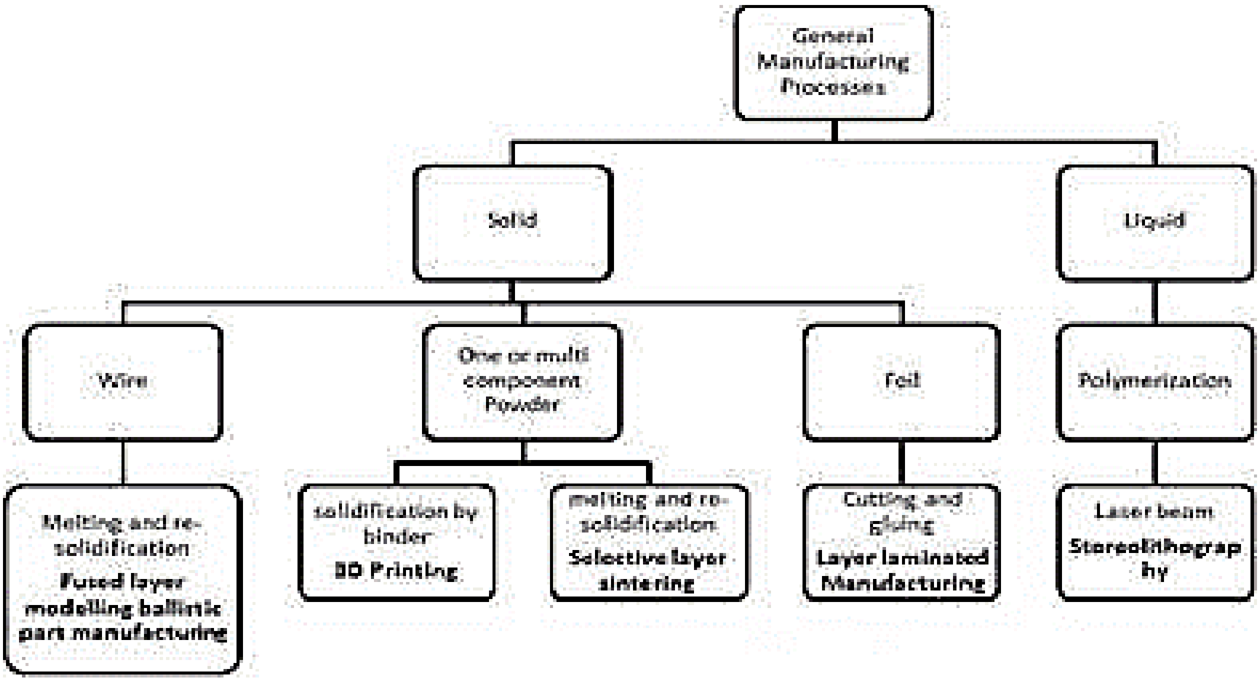

Figure 1. Flow chart of general manufacturing process.

The adaptation of 3D printing over conventional modes of fabrication has several advantages such as high precision complex geometries, design flexibility, maximal material savings and individual customization. A broad range of 3D printable materials include ceramics, alloys, metals & concrete. Acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA) are the major used polymers in the 3D printing of composites. Advanced metals and alloys are commonly used in the aerospace industry since, conventional processes are more time taking, hard to manufacture and expensive. Ceramics are commonly used for 3D printing scaffolds, used in tissue harvesting and concrete is the main material employed for additively manufacturing buildings. WinSun et al. were able to come up with 3D printed houses in mass, within a day, with $4800 USD being the cost of individual unit [2]. Additive manufacturing is able to produce components from macro to micro scale. However, there are limitations with micro to macro level printing, micro level printing presents challenges with surface finish, resolution and bonding of layers which may require some post-processing like, sintering. Anisotropic behavior & poor mechanical properties of manufactured parts possess challenges in large-scale 3D printing. More user-friendly AM oriented CAD development environments with tools to assess life-cycle cost and advanced simulation capabilities are yet to be realized. Fabrication speed and cost reduction of AM technologies can be overcome by improving machine design aspects as they inhibit the mass production.

2. LITERATURE SURVEY

The most common and commercially available methods of 3D printing employ extrusion of polymer filaments, is known as fused deposition modeling (FDM). In addition, 3D printing by elective laser melting (SLM) or liquid binding in three-dimensional printing (3DP), selective laser sintering (SLS) uses metallic powers as raw material. Also, contour crafting, inkjet printing, direct energy deposition (DED), stereolithography and laminated object manufacturing (LOM) are the major methods of additive manufacturing (AM). Novel emerging methods for definite applications like: projection micro stereolithography (PμSLA), two-photon polymerization (TPP), and electro-hydrodynamic printing (EHDP) were clarify by Mao et al. [3]; and non- contact micro and nano-printing methods were discussed by Changhai et al. [4].

2.1 Stereolithography (SLA)

SLA is one of the principals created 3D printing strategies; created by Charles Hull in 1986 [5]. SLA is utilized for delivering parts having great goals, high precision, and better surface wrap up. The printing component of SLA is clarified in (Fig 2 c). It employs UV light (sometimes electron beam) to initiate a polymerization chain reaction on a layer of monomer solution (resin). A layer is solidified when ultraviolet rays are exposed on the liquid polymer. The monomers (mainly acrylic or epoxy-based) are UV-active and instantly convert to polymer chains after activation (radicalization). Subsequent layers ranging from 0.0 5mm to 0.15 mm solidifies over preceding one inside a pattern formed after polymerization of the first layer to hold the subsequent layers and model is converted to its live form. The untreated resin is removed upon the printing completion. Sometimes, in order to achieve the desired mechanical performance post-process treatment such as photocuring or heating is used. Ceramic-polymer composites can be printed by introducing ceramic particles in resin as a dispersion [6] or ceramifiable polymer- derived monomers like silicon oxycarbide can be used as well [7]. On one hand, SLA can, 3D prints parts at a finer resolution with lower bound of 10 μm [8], but on the other, it is expensive, comparably slower and offers a limited range of 3D printable materials. In addition, kinetics of the polymerization reaction and the curing stage are complicated.

2.2 Fused Deposition Modeling (FDM)

As the name, fused deposition suggests that a liquid or molten material flow through the nozzle and is deposited in a layer-by-layer fashion forming a structure [9]. In Fused Deposition Modeling (FDM) a nozzle moves in an X-Y direction as per the requirement of the design (Fig. 1 a). The polymer is preheated slightly above its melting temperature. This is done so that it travels up to the layer. The temperature of the platform is lower so that the thermoplastic quickly becomes solid [10]. After the layer is completed, the machine sprays the wax on the layer so that it supports the structure. The most essential property for this method to work is the thermoplasticity of the polymer filament being used, which allows the fusion/ bonding of filaments together during the printing process and affects its solidification at ambient temperature upon printing operation. The process parameters affecting the mechanical properties of printed parts are the thickness of layers, width and orientation of filaments and air gap (in the same layer or between layers) [11]. Simplicity of the process, Low cost and high speed are the main advantages of FDM and makes it most commercially available 3D printing method. On the other hand, layer-by-layer appearance, weak mechanical properties, poor surface quality [12] and a limited number of thermoplastic materials are the main drawbacks of FDM [11]. The advancements in FDM has strengthened the mechanical properties of 3D printed parts by fiber-reinforced composites printing techniques [13]. However, bonding between the fiber, fiber orientation, matrix, and void formation are the major challenges faced in 3D printed composite parts [8, 13].

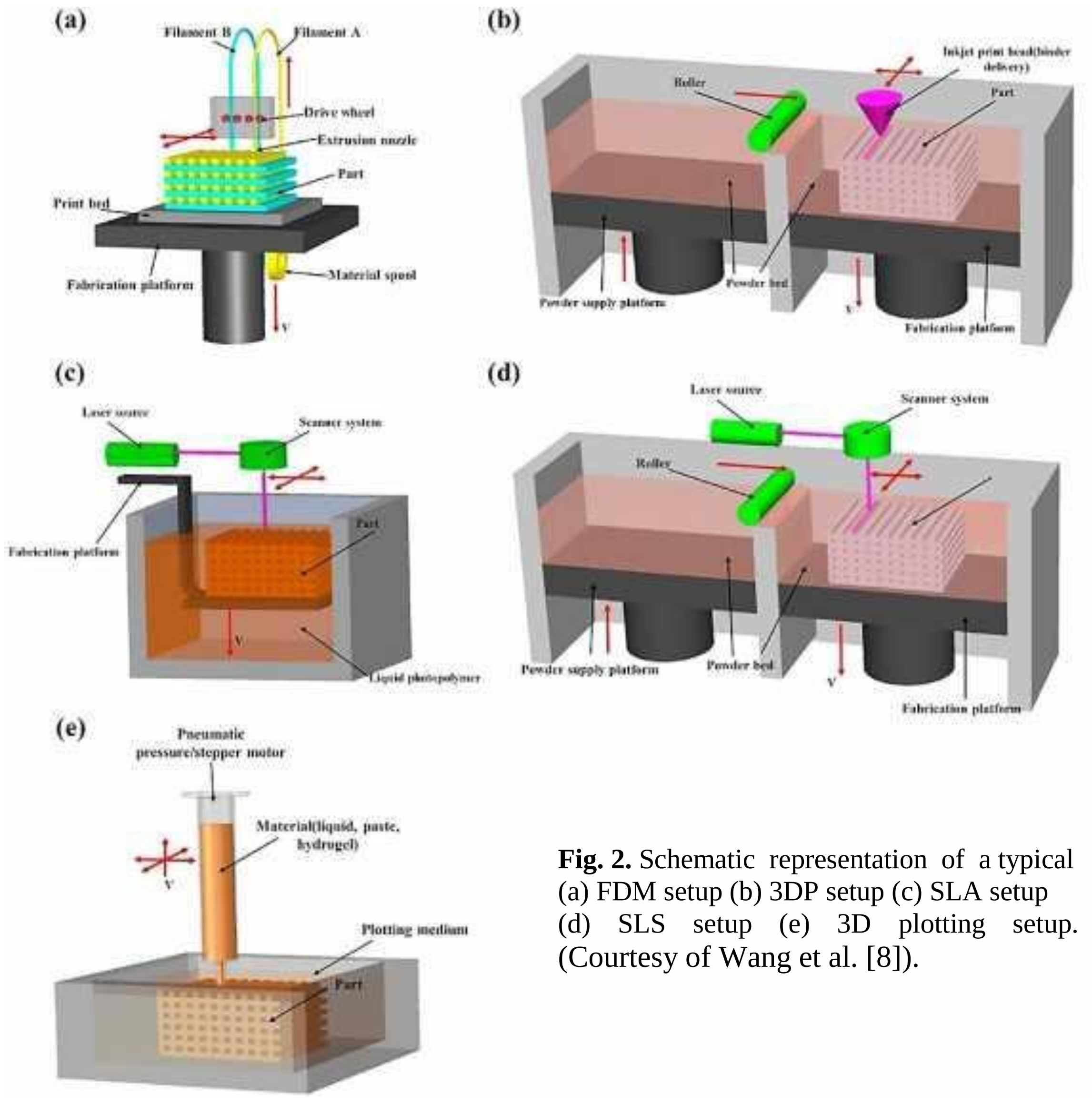

Fig. 2. Schematic representation of a typical (a) FDM setup (b) 3DP setup (c) SLA setup (d) SLS setup (e) 3D plotting setup. (Courtesy of Wang et al. [8]).

2.3 Direct energy deposition (DED)

Direct energy deposition (DED) is usually utilized for assembling elite super-combinations. This method also goes by different names like laser solid forming (LSF), laser engineered net shaping (LENS™), direct metal deposition (DMD), directed light fabrication (DLF), electron beam AM (EBAM) and wire + Arc AM (WAAM). DED uses a source of energy (laser or electron beam) which is focused on a small region of the substrate and is used to melt a feed material (powder or wire) at the same time. The liquefied material is then intertwined into the softened substrate and cements after the development of the laser bar [14]. The DED and SLM methods are differentiated in a way that DED uses no powder bed and similar to FDM the feed material is melted before deposition in a layer-by-layer form but with an extremely higher amount of energy for melting metals. Therefore, this method is useful for retrofitting and crack filling of the manufactured parts for which the application of the powder-bed method is limited. Furthermore, to complete machining DED can easily be combined with traditional subtractive processes. In general, this technique is used with Inconel, titanium, stainless steel, aluminum and the related alloys for aerospace applications. The process is characterized by high speeds (from 0.5 kg/h for LENS [15] to 10 kg/h for WAAM [16]) and very large work envelopes (up to 6 m × 1.4 m x 1.4 m for commercial printers) [17]. However, it has a lower surface finish, lacks accuracy (0.25 mm) and is not able to manufacture complex parts compared to SLM or SLS [14]. Thus, DED is frequently employed for refurbishing larger components and for large components with less complexity. DED can cut down the production time and cost, and contributes to excellent mechanical properties, precise composition control, and controlled microstructure.

2.4 Powder bed fusion

Powder bed fusion is a powder-based 3D printing process. The powders in each layer are fused together with a laser beam or a binder, which are spread and closely packed on a platform. Consecutive powder layers are rolled over and processed until structure takes its final shape (Fig. 1 d). The excess powder is then withdrawn using a vacuum and if required, post-processing and detailing such as coating, sintering or infiltration are carried out. Packing and distribution of particles, which governs the density of the part, are the most essential factors to the potency of this method [18]. Powders with a low melting/sintering temperature are only treated with lasers else liquid binder is used followed by post processing techniques. A variety of polymers, metals and alloy powders are compatible with Selective laser sintering (SLS), whereas selective laser melting (SLM) can only be used with selective metals such as aluminum and steel. Complete melting of power does not occur in SLS rather fusion of the powder at the molecular level exists because of elevated temperature at the grain surface. On the other hand, SLM results in superior mechanical properties as the powder is completely melted and properly fused together [19]. The case when a liquid binder is used, the method is referred to as three-dimensional printing or 3DP. The rheology and chemistry of the binder, size and shape of powder particles, the interaction between the powder and binder, deposition speed and post-processing techniques play a vital role in 3DP [8,18]. Parts printed using binder deposition shows more porosity in comparison to the dense parts printed using SLM or SLS [18]. Scanning speed and power of laser used are the major process parameters affecting the sintering process. Powder-based fusion methods are widely used for scaffolds for tissue engineering, lattices, aerospace applications and electronics as it produces parts with finer resolution, greater accuracies and high built quality. Powder bed acts as support material and is easy to remove after completion of printing. However, this process is slow, costly and high porosity is observed in the case of resin usage.

2.5 Inkjet printing and contour crafting

Inkjet printing is one of the best methods for the additively manufacturing ceramics. It is currently used for manufacturing sophisticated and complex ceramic structures for advanced applications such as scaffolds for tissue engineering. In this method, a stable suspension of ceramic particles such as zirconium oxide powder in water [20] is pumped and deposited in the form of droplets through the injection nozzle onto the substrate. These droplets then solidify in a continuous pattern to offer sufficient strength in a manner to hold consecutive layers (Fig. 1 b). This method is fast and efficient, which adds flexibility for designing and printing complex structures. Two major types of ceramic inks are wax-based inks and liquid suspensions. Wax- based inks, in order to solidify, upon melting are deposited on a cold substrate. While liquid evaporation causes solidification of liquid suspensions. The viscosity of the ink, size distribution of ceramic particle, solid content, as well as the rate of extrusion, size of nozzle and printing speed, are factors governing the standard of inkjet-printed parts [6]. Lack of inter-layer adhesion, low resolution and maintaining workability, are the main constraints of this method. Contour crafting is a similar process to inkjet printing, is capable of extruding soil or concrete paste using larger nozzles under high pressure and thus, is the main method for additively manufacturing large building structures. The method of contour crafting has been prototyped successfully to be used for construction on the moon [21].

2.6 Laminated object manufacturing (LOM)

Laminated object manufacturing (LOM) is one of the first commercially available additive manufacturing methods. In LOM sheets or rolls of materials are cut precisely using a mechanical cutter or laser and then laminated together (form-then-bond) or vice versa (bond-then-form) in a layer-by-layer fashion. The form-then-bond method is specifically useful for thermal bonding of metallic and ceramics materials, which also aids in the construction of internal features by eliminating excessive materials before bonding. The eliminated material is left to provide supports and then can be further recycled [22]. A wide variety of materials including ceramics, paper, polymer composites and metal filled tapes can be used with LOM. Post-processing techniques like high-temperature treatment can be adopted according to the type of materials and desired properties. A new subdivision combines ultrasonic metal seam welding and CNC milling in the lamination process, known as Ultrasonic additive manufacturing (UAM) [23]. UAM is only AM process that is capable to construct metal structures at low temperatures [24, 25]. Laminated object manufacturing can be observed in the foundry industries, paper manufacturing industries, smart structures, and electronics industries. Electronic devices can be printed in the same lamination process, unlike conventional methods, for embedded electronic devices, sensors, pipes and other features the user can define cavities in the structure based on the integrated computer design using direct write technologies [22]. For larger structures, LOM can be described as one of the best methods because of its ability to significantly reduce the tooling cost and manufacturing time. Whereas, without post-processing methods, the process produces an inferior surface finish. In addition, it produces lower accuracy components also; eliminating the excess parts of laminates upon printing is time taking in comparison to powder-bed methods. Thus, manufacturing of complex geometries is not suggested using this technique.

3. CURRENT TRENDING APPLICATION OF 3D PRINTING

3.1 Biomedical industry

Biomedical industry is one the rapid growing area in Additive manufacturing. The biggest challenge in biomedical industry is the complexity of the products such as biomedical implants tissues and organs Using Additive manufacturing techniques such complex parts can be produced using novel materials such a semi-crystalline polymeric composites [26][27]. Additive manufacturing is more cost-effective and produces faster prototypes compared to conventional manufacturing methods like molding milling, casting and forging. Bio fabrication involves the generation of tissues and organs via bioprinting , bio assembly and maturation.

3.2 Aerospace Industry

According to Wohlers report [28] 18% of total Additive manufacturing market contribution is from the aerospace industry. Additive manufacturing has proven to be important for this industry and some of the important reasons why Aerospace is a promising industry for additive manufacturing are:

Complex Geometry: Additive Manufacturing processes generally make complex parts involving many intricate parts easily. In 2016, GE aviation developed the fuel nozzles for its new LEAP family of engines using direct metal laser melting. By 3D printing the part the weight of the nozzles came down by 25 percent, the number of the parts used to create the nozzle to be reduced from 18 to 1, also with the help of AM we could make more intricate cooling pathways and supports, giving the nozzle a five-fold increase in durability [29].

Waste Reduction: By using, AM techniques in aerospace industry we can reduce the amount of waste produced in manufacturing of advanced and costly material such as titanium alloys, nickel- based super alloys or ultra-high temperature ceramics

Customized production: The introduction of additive manufacturing will help by increasing customized production of goods and can reduce the problem of storing of manufactured product, by on demand manufacturing which will eliminate the use of inventory and its maintenance.

Metallic and non-metallic (such as metamaterials [30, 31]) parts can be manufactured or repaired using AM such as aero engine components, turbine blades and heat exchangers. Non-metal AM methods such as stereolithography, multi-jet modelling [32] and fused deposition modelling (FDM) are used for the rapid prototyping of parts and for manufacturing fixtures and interiors made of plastics, ceramics and composite materials.

Direct Energy deposition (DED) is less accurate than Power bed fusion and is used in manufacturing large structural components. The accuracy comparison of DED and PBF is 1mm vs 0.05mm respectively [33]. ‘Norsk Titanium As’ manufactured titanium structural part for Boeing 787 by ‘Rapid Plasma Deposition’ in melting of titanium wire happens inside a gas chamber filled of argon gas. This resulted in reduction of manufacturing cost of the aircraft by $2 to $3 million [34].

The high accuracy of Powder Bed Combination (PBF) technologies takes into consideration the streamlining of segment design and integration with different capacities. This system is utilized for the most part for littler parts with higher multifaceted nature. The sections produced for the Airbus A350 XWB are 30% lighter and diminished the manufacturing time by around 75%

High-execution aviation segments are made of costly materials with cutting edge and complex manufacturing strategies [35]. These parts are additionally subjected to erosion, effects, stretch and rehashed warm cycles that can generate imperfections or splits. As these parts are to a great degree costly, substitution is more ideal than repair. On the other hand, AM technologies can repair high-esteem metal segments with high accuracy and little generation of warmth contrasted with ordinary welding forms [36]. A laser bar makes metallurgical securities between the part (i.e., the substrate) and the additional repair metal (i.e., the powder). This system generates negligible twists furthermore, can be utilized for perplexing and thin-walled aviation parts. Likewise, "non-weldable" materials or bending touchy parts can be repaired with AM.

3.3 Construction

Wohlers' report demonstrates that the structural applications speak to just 3% of the aggregate AM industry [28]. In any case, this part is in its early stages as it was utilized for private structures just from 2014 and has demonstrated great potential from that point forward [37]. Computerized building development with 3D printing technology has gained increasing consideration as of late. It can conceivably upset the development industry and it can offer space explorers less demanding development on the moon [38]. It offers a significant decrease in development time and labor [2]. The customary methods utilized in the development business are casting, molding and expulsion. The utilization of 3D printing in the building industry can be used in zones where there are requirements, for example, geometric complexities and empty structures. Henceforth, its unwavering quality is because of its capacity to create with high accuracy and opens up different design conceivable outcomes. Khoshnevis built up the form crafting (CC) technology for the mechanized development of buildings also, foundation, and for space applications [19]. Because of its capacity to use in-situ materials, it can be promptly utilized for the development of low-wage housing and for building covers on the moon. The initial 3D printed private structure was produced in Amsterdam in 2014, where the FDM technique was used (Fig. 2) [37]. The undertaking was pushed through by draftsmen from Dus Architects, who needed to illustrate the portability of the printer with insignificant material wastage also, transportation costs, in this manner paving its way to the building business. It was likewise in 2014 when WinSun, an engineering firm in China, mass printed private houses in Shanghai in under 24 hr. Customary 3D printers limited the utilization of this technology in the business because of its size. Be that as it may, a 3D printer with a size of 150m x 10m x 6.6m was utilized in this undertaking, which utilized concrete and glass fiber. A portion of the challenges experienced by WinSun throughout the length of the task incorporates issues with fragility, integration of building administrations and circuitous printing [2].

The contour crafting method, which is a robot or crane-mounted can be likewise utilized for on- location applications. Nadal [39] additionally outlined the methods used to scale up to a run of the millwork area 3D printing into two primary strategies: 1) bridge crane methodologies and 2) techniques similar to CC. Be that as it may, a few challenges are experienced when these strategies are directed off-site, for example, 9material wastage and imprecisions that tend to be more work escalated [39]. Hager et al. utilized a promising system like CC technology, which utilizes cementitious materials, thermoplastics, and artistic items, which can change the development industry later on. CC technology can print layers nearby, along these lines enabling the printing of large parts with boundless adaptability and accuracy.

The material that was used initially for onesie CC construction is a mixture of cement and sand. The D-shape method, on the other hand, utilizes the powder deposition process where a chemical agent, such as a chlorine-based liquid, is used to bind the powder (e.g., sand or stone powder). Since raw materials and manufacturing process utilizing 3D printing are different from ordinary construction techniques, the need for skilled workers with the capacity to incorporate both automated and common cooperate stays another obstacle for AM in the construction business [40].

4. CURRENT MARKET OF 3D PRINTING

Current market of 3D printing stands for about $7.3 billion according to the eponymous wohlers report 2018 which is predicted to grow to $32.78 billion by 2023 according to the report "3D Printing Market by Offering (Printer, Material, Software, Service), Process (Binder Jetting, Direct Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion), Application, Vertical, and Geography - Global Forecast to 2023"

According to a research report by UPS and the Consumer Technology Association (CTA) in their report “3D Printing: The Next Revolution in Industrial Manufacturing” western countries contributes to two-thirds (68%) of the 3D printing revenue while Asia pacific has a share of 27%

, where out of this 68% splits into 40 % from North America and 28% from Europe. When it comes to the industry wise share the consumer and automotive industries contribute 20% of the total revenue generated by 3D printing Industry. Medical Industry is the third largest contributor to 3D printing industry with a revenue share of 15%. The major use of 3D printing goods has been in Functional Part, Fit and finish component, Molds and tooling and visual proof or concept. Steel and plastic were the most used 3D printing material in 2016 where Plastic hold the first and steel hold the second position. We have also observed an increasing growth of biomaterial in 3D printing industry and other materials like lay wood wax and paper are being used. Construction sector is also growing rapidly in 3D printing industry.

5. CONCLUSION

This paper provides an overview of different Rapid Prototyping technology in deep and emphasized on their ability to shorten the product design and development process. Rapid manufacturing will never completely replace other manufacturing techniques, especially in large production runs where mass production is more economical. Rapid prototyping is swiftly developing technologies for manufacturing the different products by adding or removing material in the layer-by-layer formation. Rapid Prototyping provides free from the fabrication of the complex geometry directly from their CAD models automatically. Rapid Prototyping changes the way companies design and builds products. In future speed improvement should be done in RP to make them economical for the wider diversity of commodity. One more important development for Rapid Prototyping is to increase size capacity. At present, most Rapid Prototyping machines are restricted to objects of 0.125 cm3 or less.

ACKNOWLEDGEMENT

This work was supported by HP CSR Initiative, catalyzed by Drstikona and implemented by Nalanda Foundation. The authors are thankful to other stakeholders of this program including Leadership, and Faculty Mentors at IIT-BHU.

REFERENCES

[1] Berman, B., 2012. 3-D printing: The new industrial revolution. Business horizons, 55(2), pp.155-162.

[2] Wu, P., Wang, J. and Wang, X., 2016. A critical review of the use of 3-D printing in the construction industry. Automation in Construction, 68, pp.21-31.

[3] Mao, M., He, J., Li, X., Zhang, B., Lei, Q., Liu, Y. and Li, D., 2017. The emerging frontiers and applications of high-resolution 3D printing. Micromachines, 8(4), p.113.

[4] Ru, C., Luo, J., Xie, S. and Sun, Y., 2014. A review of non-contact micro-and nano-printing technologies. Journal of Micromechanics and Microengineering, 24(5), p.053001.

[5] Melchels, F.P., Feijen, J. and Grijpma, D.W., 2010. A review on stereolithography and its applications in biomedical engineering. Biomaterials, 31(24), pp.6121-6130.

[6] Travitzky, N., Bonet, A., Dermeik, B., Fey, T., Filbert‐ Demut, I., Schlier, L., Schlordt, T. and Greil, P., 2014. Additive manufacturing of ceramic‐ based materials. Advanced Engineering Materials, 16(6), pp.729-754. [7] Eckel ZC, Zhou C, Martin JH, Jacobsen AJ, Carter WB, Schaedler TA. Additive manufacturing of polymer-derived ceramics. Science 2016; 351(6268):58 –62.

[8] Wang, X., Jiang, M., Zhou, Z., Gou, J. and Hui, D., 2017. 3D printing of polymer matrix composites: A review and prospective. Composites Part B: Engineering, 110, pp.442-458.

[9] Pandey, P.M., 2010. Rapid prototyping technologies, applications and part deposition planning. Retrieved October, 15, pp.550-555..

[10] Mahindru, D.V., Priyanka Mahendru, S.R.M.G.P.C. and Ganj, T., 2013. Review of rapid prototyping-

technology for the future. Global journal of computer science and technology..

[11] Mohamed, O.A., Masood, S.H. and Bhowmik, J.L., 2015. Optimization of fused deposition modeling process parameters: a review of current research and future prospects. Advances in Manufacturing, 3(1), pp.42-53.

[12] Chohan, J.S., Singh, R., Boparai, K.S., Penna, R. and Fraternali, F., 2017. Dimensional accuracy analysis of coupled fused deposition modeling and vapour smoothing operations for biomedical applications. Composites Part B: Engineering, 117, pp.138-149.

[13] Parandoush, P. and Lin, D., 2017. A review on additive manufacturing of polymer-fiber composites. Composite Structures, 182, pp.36-53.

[14] Edgar, J. and Tint, S., 2015. Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. Johnson Matthey Technology Review, 59(3), pp.193-198.

[15] https://www.optomec.com/wp-content/uploads/2014/.../LENS_850-R_Web_0716.pdf

[16] Williams, S.W., Martina, F., Addison, A.C., Ding, J., Pardal, G. and Colegrove, P., 2016. Wire+ arc additive manufacturing. Materials Science and Technology, 32(7), pp.641-647.

[17] http://www.sciaky.com/largest-metal-3d-printer-available

[18] Utela, B., Storti, D., Anderson, R. and Ganter, M., 2008. A review of process development steps for new material systems in three dimensional printing (3DP). Journal of Manufacturing Processes, 10(2), pp.96-104.

[19] Lee, H., Lim, C.H.J., Low, M.J., Tham, N., Murukeshan, V.M. and Kim, Y.J., 2017. Lasers in additive manufacturing: a review. International Journal of Precision Engineering and Manufacturing- Green Technology, 4(3), pp.307-322.

[20] Dou, R., Wang, T., Guo, Y. and Derby, B., 2011. Ink- Jet Printing of Zirconia: Coffee Staining and

Line Stability. Journal of the American Ceramic Society, 94(11), pp.3787-3792.

[21] Khoshnevis, B., 2004. Automated construction by contour crafting—related robotics and information technologies. Automation in construction, 13(1), pp.5-19.

[22] Edgar, J. and Tint, S., 2015. Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. Johnson Matthey Technology Review, 59(3), pp.193-198.

[23] Li, J., Monaghan, T., Nguyen, T.T., Kay, R.W., Friel, R.J. and Harris, R.A., 2017. Multifunctional metal matrix composites with embedded printed electrical materials fabricated by ultrasonic additive manufacturing. Composites Part B: Engineering, 113, pp.342-354.

[24] Hahnlen, R. and Dapino, M.J., 2014. NiTi–Al interface strength in ultrasonic additive manufacturing composites. Composites Part B: Engineering, 59, pp.101-108.

[25] Hehr, A. and Dapino, M.J., 2015. Interfacial shear strength estimates of NiTi–Al matrix composites fabricated via ultrasonic additive manufacturing. Composites Part B: Engineering, 77, pp.199-208.

[26] Ventola, C.L., 2014. Medical applications for 3D printing: current and projected uses. Pharmacy and Therapeutics, 39(10), p.704-711.

[27] Garcia-Gonzalez, D., Garzon-Hernandez, S. and Arias, A., 2018. A new constitutive model for polymeric matrices: Application to biomedical materials. Composites Part B: Engineering, 139, pp.117- 129.

[28] Wohlers, T., 2014. 3D printing and additive manufacturing state of the industry. Annual Worldwide Progress Report. Wohlers Associates.

[29] https://www.technologyreview.com/s/426391/layer-by-layer/.

[30] Yin, L., Doyhamboure, J., Tian, X. and Li, D., 2018. Design and characterization of radar absorbing structure based on gradient-refractive-index metamaterials. Composites Part B: Engineering, 132, pp.178-187.

[31] Turco, E., Golaszewski, M., Giorgio, I. and D'Annibale, F., 2017. Pantographic lattices with non-orthogonal fibres: experiments and their numerical simulations. Composites Part B: Engineering, 118, pp.1-14.

[32] Chua, C.K., Leong, K.F. and Lim, C.S., 2003. Rapid prototyping: principles and applications (Vol. 1). World Scientific.

[33] http://us.dmgmori.com/blob/354972/caef73fe2f4d3e0baff239006d465164/pl0us-lasertec-65-3dpdf.

[34] http://www.norsktitanium.com/media/press/norsk-titanium-to-deliver-the-worlds-first-faa- approved-3d-printed-structural-titanium-components-to-boeing.

[35] Dey, N.K., 2014. Additive manufacturing laser deposition of Ti-6Al-4V for aerospace repair application, https://scholarsmine.mst.edu/masters_theses/7295/.

[36] Graf, B., Gumenyuk, A. and Rethmeier, M., 2012. Laser metal deposition as repair technology for stainless steel and titanium alloys. Physics Procedia, 39, pp.376-381..

[37] 3D Print Canal House – DUS Architects. http://houseofdus.com/project/3d-printcanal- house/. 23/10/2017.

[38] Labeaga-Martínez, N., Sanjurjo-Rivo, M., Díaz-Álvarez, J. and Martínez-Frías, J., 2017. Additive manufacturing for a Moon village. Procedia Manufacturing, 13, pp.794-801.

[39] Nadal, A., Pavón, J. and Liébana, O., 2017. 3D printing for construction: a procedural and material- based approach. Informes de la Construcción, 69(546), p.e193.

[40] Hager, I., Golonka, A. and Putanowicz, R., 2016. 3D printing of buildings and building components as the future of sustainable construction? Procedia Engineering, 151, pp.292-299.