A review of rapid prototyping and its applications

Purushottam Sharma, Dheeraj Joshi, Ajay Dhanopia, Mahesh Sharma
Department of Mechanical Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan Jaipur-302017 (INDIA)
Email: erpurushottamsharma@gmail.com
Received 17.07.2019 received in revised form 09.01.2020, accepted 11.01.2020

Abstract- Rapid prototyping (RP) is one of the fabrication processes known to have inherent rapidity and flexibility in its operation. It defines as a group of techniques that refers to the layer-by-layer fabrication of physical models three-dimensional (3D) directly from a computer-aided design (CAD). The paper focuses on basic steps in RP technique which include creating a CAD model and converting it to Standard Tessellation Language (STL) file format, slicing the STL file, layer by layer fabrication, cleaning and finishing the part. In recent years, increased use of computers has been visualized in CAD, Computer Aided Manufacturing (CAM) and Computerized Numerical Control (CNC) machine tools. Various prominent RP techniques such as Stereolithography (SL), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM) etc. have been discussed in sufficient length. SL which is based on photo-polymerisation or photo-curing and synthesis of polymers initiated upon the absorption of ultraviolet (UV) or visible light by a polymerisable system. SLS process uses powder material and CO2 laser is used for scanning and sintering of a part. Another popular technique, FDM works on melting and solidification principle. LOM observes layer-by-layer lamination of paper material sheets using a CO2 laser; each sheet represents one cross-sectional layer of the CAD model of the part. The applications of the RP have also been comprehensively described in various fields such as aerospace industry, automotive industry, biomedical industry, and electronic industry.
Keywords – CAD, Rapid prototyping, STL.

1. INTRODUCTION

One of the most significant steps in completing product design is prototyping. It helps in the formulation and testing of a product for imperfections during various aspects of its design. Rapidity and flexibility are two paramount aspects of any design which aims that new products and dissimilarities within the product families are tackled and produced in quick time. Rapid prototyping (RP) is one of the fabrication processes which is known to have inherent rapidity and flexibility in its operation. It defines as a group of techniques that refers to the layer-by-layer fabrication of physical models three-dimensional (3D) directly from a computer-aided design (CAD) [1]. Various RP techniques have been developed to quickly produce physical prototypes to reduce the time to market of new products [2-3]. With the advent of CAD/CAM technologies, there is a phenomenal growth in RP methods for last three decades. It has been easier to create solid models with knitted information of edges and surfaces for defining a product [4]. Compared to traditional (Computerized Numerical Control) CNC machining, RP technologies have advantages over the creation of complex part geometries in a reasonable time. Moreover, some shapes such as self-reentrant structures, internal voids which are impossible for traditional manufacturing etc. can be conveniently handled by RP techniques [5]. The major benefit of RP technology is that process planning is extremely simple and can be applied to parts with almost any geometry without any changes (creating a cross section is simple regardless of 3D complication). It is thus possible to produce specific or highly customized parts with high dimensional complexity using diverse technologies and various materials available in the RP family. Another significant advantage is the possibility to construct parts with a lightweight internal structure or to use a targeted component design [6]. Therefore, the great time saving of RP is due to the simple and automatic process engineering preparation for each part instead of the actual speed of the process itself. The development of RP in manufacturing industries continues to accentuate the following:

- The increasing number of variants of products and product complexity.
- Decreasing product lifetime before obsolescence and the delivery time of the product.
- RP advances product development by introducing better communication in a concurrent engineering environment [7].

There are several popular RP techniques employed by practitioners and users. One of the RP techniques is 3D printing that prints an adhesive on a powder bed to generate parts in an incremental manner[6]. In another method named as stereolithography (SL) process, photosensitive resins solidify with a (Ultraviolet) UV light [8] to get the required part. A high power laser beam is used to fuse or fabricate small particles of plastic, metal or ceramics in Selective Laser Sintering (SLS) process. There are also some other RP techniques prevailing in industries which have been discussed later. However, as new RP technologies emerge along with increasing demands of niche markets, it can only be a matter of time before other prototyping techniques gain widespread acceptance [9].

There are, of course, some limitations of conventional RP methods in the sense that it provides limited part accuracy which is imposed by several issues like forming processes, internal stresses, also post-processing is required. The limitation with the existing materials has kept RP technologies from being used in the manufacturing of actual functional parts. Readily available materials in RP are thermoplastic or photopolymer materials, liquid resin, ceramics and metal or other powders to be processed.

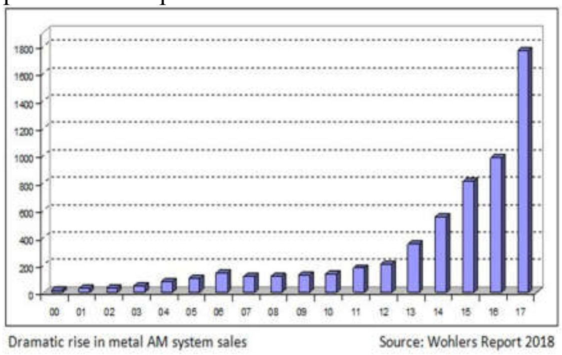

Figure 1: Wohler's Report 8 [10]

Figure 1 depicts the Wohler's Report 2018 in which it can be seen that there has been a dramatic rise in metal Additive Manufacturing system sales wherein overall industry growth has been up to 21%. Seventy-six co-authors and contributors from various countries shared data and expertise to form the basis of analysis in Wohler's Report 2018 [10]. Global companies are increasingly becoming conscious of the advantages of additive manufacturing of metal components. It is essential to note that the additive manufacturing (AM) and 3D printing industry terms have been used interchangeably in this paper.

We present a state-of-the-art review of rapid prototyping techniques and their applications in this article. In the next section, we discuss the historical development of RP technologies. In Section 3, the necessary steps to accomplish the RP have been discussed. These steps are, to a large extent, generic in nature and can be slightly customized as per the specific RP process. Subsequently, in Section 4, the important RP techniques have been discussed to get an insight into the processes. In Section 5, the prominent applications and key areas have been highlighted where RP technologies find their typical use. As an outcome of this paper, we bring out some key issues and critical factors that need to be considered by researchers for enhancing the effectiveness and applicability of various RP techniques. Finally, conclusions of this paper in the context of RP have been made in Section 6.

2. HISTORICAL DEVELOPMENT OF RP

RP technology, which is nearly three decades old, is closely related to the development and applications of computers in the industry. More specifically, increasing in the use of computers had encouraged the improvement in many areas related to computer including CAD, CAM and CNC machine tools. Stereolithography, which was the first RP technique, developed by the company 3D Systems of Valencia, CA, the USA in 1984, and since then various RP techniques have been obtained. A brief historical development of RP and related technologies is presented in Table 1.

Table 1: A brief history of the development of RP and its related technologies [11]

Yearly inception	Technology
1770	Mechanization
1946	First computer
1952	First NC machine tool
1960	First commercial Laser
1961	First industrial robot
1963	Introduction of CAD
1980	The patent on Rapid Prototyping
1984	Stereolithography (SL)
1988	The first commercial RP system
1988	Fused deposing modelling
1989	Selective Laser Sintering
1993	3D printing
1995	Selective laser melting

There have been three prominent phases that can be attributed to the growth of RP techniques. These have been discussed in what follows next [12].

2.1 Phase I: Manual Prototyping

Prototyping had begun to develop tools to help them to fabricate parts. In this phase, prototypes usually were not very sophisticated as well as fabrication of prototypes took about four weeks on average or a month, depending on the type of complexity and representativeness. The techniques used in manufacturing these prototypes had a tendency to be craft-based and were typically extremely labor intensive.

2.2 Phase II: Virtual Prototyping

As the advancement of CAD /CAM became more prevalent in this second phase of prototyping, i.e. soft or Virtual Prototyping, more computer tools became available, and computer models could then be stressed out, tested, analyzed and modified as if they were physical models. Stress and strain analysis can be accurately predicted on the product because of the ability to specify the attributes and properties of the exact material. With these tools on the computer, several iterations of designs can be easily carried out by changing the parameters of the CAD models. Also, the products and as such, that types of prototypes tend to become relatively more complex about twice the complexity as before [9]. Lee [10] argues that RP still has inevitable limitations, including material limits. Within the implementation of kinematic/dynamic analysis, little or no reliable information can be collected from the rapid prototype to conduct finite element analysis; he outlined a program that can assign physical characteristics to many distinct materials, such as steel, plastic, etc.

2.3 Phase III: RP

RP of physical parts, also known as solid freeform fabrication or layer manufacturing technology, represents the third phase in the succession of prototyping. The invention of this succession of RP methodologies is described as a "watershed event" [13] for a reason that of the great time savings, especially for intricate models or parts. Though the parts which are individuals as the components are somewhat three times as complex to the parts made in 1970’s, the time to make such a part is required at present averages of only three weeks. Since 1988, various RP techniques have emerged.

3. BASIC STEPS OF RP

RP works based on adding layers of material to form the desired shape. The majority of commercial RP system build an object by adding one layer after another.

Figure 2 shows the flow process typically employed in an RP method. These steps have been explained in detail in what follows next.

3.1 Creation of CAD Model

At first, the object to be built is modelled using a CAD software package. A large number of software packages are available in the market like PRO/ENGINEER. These tend to represent 3D models more accurately than the wireframe modellers such as AutoCAD and hence produce very good results. The designer creates a new file specifically for the prototype or may use the existing CAD file. This process is the same for all the RP techniques.

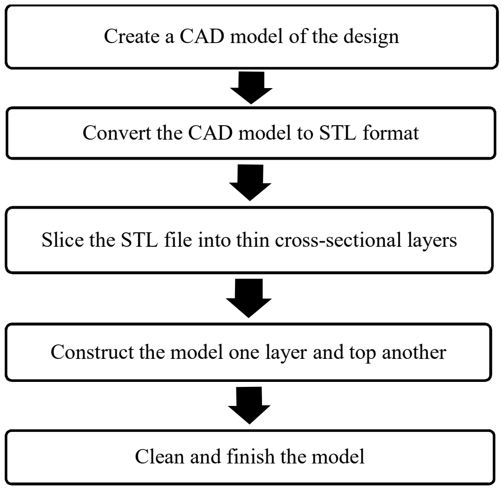

Figure 2: Flow process of an RP method

3.2 CAD model Conversion to STL File Format

The second step, solid parts are converted the CAD file into Standard Tessellation Language (.STL) format which is compatible with the RP machine [14]. RP machine software receives CAD model data into .STL format and creates a complete set of information to fabricate model on the RP machine, for instance, tool path, layer thickness, raster angle, fabricating speed, etc. Several different algorithms are used to represent solid objects from the various CAD packages. To establish reliability, the .STL file format was accepted as the RP industry's usual format for determining consistency.

Apart from .STL, there are other translators which are used to improve design data such as IGES

(Initial Graphics Exchange Specification) file which is used to switch graphics information between commercial CAD systems [15]. Among other formats, CT (Computerized Tomography) scan data is a particular approach for medical imaging [16]. HP/GL (Hewlett-Packard Graphics Language) is a standard data format for graphic plotters [17]. The CLI (Common Layer Interface) format is [18] meant as a vendor-independent format for layer by layer manufacturing technologies. The SLC (Stereolithography Contour) file format [19] addresses many problems associated with .STL file format. The RPI (RP Interface) format is capable of representing facet solids, but it includes additional information about the facet topology [20].

3.3 Slice the STL File

In this step, a pre-processing program prepares .STL file which is to be built by placing the shortest dimension in the direction of reducing the number of layers, thereby decreasing build time. Several programs are available, and most of these allow the user to adjust the size, position and fabricating direction of orientation of the model.

3.4. Layer by Layer Fabrication

This step corresponds to the actual fabrication of the part. RP machine is used as a hardware device to manufacture the object using the layer manufacturing method. Using one of the numerous techniques, RP machines fabricate one layer at a time from polymer resins, paper, or powdered metals and subsequently build a layer over layer to fabricate the required part.

3.5 Clean and Finish

This is the last step in which post-processing is done, and that involves removing the prototype from the machine and detaching any supports. Prototypes may also require some minor cleaning and surface treatment like sanding, sealing or painting to improve the appearance and durability of the model. A 3D model, after removing support material in the post-processing treatment process, is the final product.

Table 2: Classification of RP processes [21]

tate of starting material	Technologies	Substrate	Mechanism of layering
Binder jetting	• Powder bed inkjet printing, S-printing • M-printing • Theriform • Zip Dose	Solid particles (plaster, metal, sand, polymer)	To join powder materials, a liquid binding agent is selectively deposited.
Vat polymerization	• Stereolithography (SL) • Digital light projection(DLP) • Continuous layer interface production(CLIP)	Liquid (photopolymer)	With light-activated polymerization, liquid photopolymer in a vat is selectively cured.
Powder bed fusion	• Selective laser sintering(SLS) • Direct metal laser sintering (DLSM) • Selective metal sintering(SLM) • Electron beam melting(EBM) Concept laser	Solid particles (metal, plastic, polymer)	Thermal energy fuses the regions of a powder bed selectively.
Material extrusion	• Fused deposition modelling (FDM) • Gel/paste extrusion	Filament (thermoplastic polymers, e.g. ABS; PLA; PC ULTEM)	Through a nozzle or orifice, the material is selectively dispensed.
Material jetting	• Ink-jet printing • Poly jet • Thermo jet	Liquid (acrylic-based photopolymers, Elastomeric photo polymers, wax-like materials)	Droplets of built material are selectively deposited.
Directed energy deposition	• Electron beam direct Manufacturing • Direct metal tooling(DMT) • Be-additive manufacturing (BeAM)	Wire (metal)	Focused thermal energy is used as deposited to fuse materials by melting.
Sheet lamination	• Laminated Object Manufacturing	Sheets	Material sheets are bonded to form an object.

4. RP TECHNIQUES

In this section, we present various prominent RP techniques used by practitioners for fabricating products of domestic and industrial use. Table 2 shows the classification of RP processes according to the type of materials, substrate and mechanism of layering used [21].

ASTM classified these processes into seven categories of machines based on the additive type namely binder jetting, material extrusion, material jetting, powder bed fusion, vat photopolymerisation, directed energy deposition and sheet lamination. Some of the popular techniques based on these types of processes have been reviewed below.

4.1 Stereolithography

Stereolithography (SL) is based on photo-polymerisation or photo-curing, which is commonly defined as the synthesis of polymers initiated upon the absorption of UV or visible light by a polymerisable system. In this process, rapid conversion of solvent-less liquid compositions into solid films occurs. Light serves only as an initiating tool, and it does not interfere with the propagation and termination stages of the polymerization process [22]. Due to the absorption and scattering of the beam, a reaction only takes place near the surface, and volume pixels or voxels of solid polymeric resin are formed. An SL machine consists of a build platform (substrate), which is mounted in a vat of resin and a UV Helium, Cadmium or Argon ion laser. The first layer is scanned by the laser after this platform is down to one slice layer thickness. After some time liquid polymer settled in a flat form and prevent bubble formation. The new slice is then scanned. Schematic diagram of the Stereolithography process is shown in figure 3.

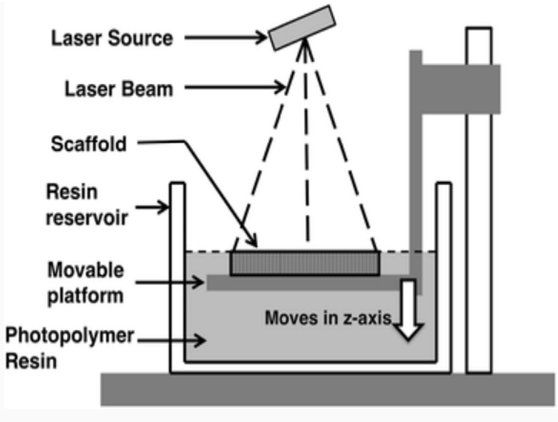

Figure 3: Stereolithography Process [23]

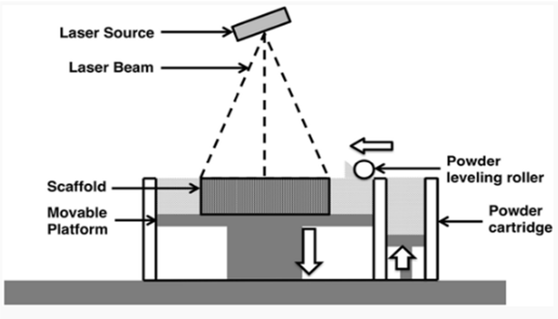

Figure 4: Selective Laser Sintering [23]

4.2 Selective Laser Sintering

Selective Laser Sintering (SLS) process uses powder material like polycarbonate, polystyrene or polyamide etc. (20 to 100 µm diameter) is spread on the surface using a roller. To minimize the effect of thermal distortion and facilitate fusion to the former layer, raise the temperature of the entire bed by infrared heating just below its melting point temperature before starting laser scanning. The CO_2 laser is used for scanning and sintering of a slice. The laser is controlled in such a way that only those layers, which are in direct contact with the beam, are affected.

4.3 Fused Deposition Modeling

In Fused Deposition Modeling (FDM) process works on melting and solidification principle. In this process, the molten polymeric material is deposited by the heated nozzle. Whereas the heated nozzle is capable of moving in x-y-z-direction to the fabrication of the part. The build material passes through a heated nozzle, which temperature above the melting point and deposited in the predefined path so that it solidifies within a very short time (approximately 0.1 s) after extrusion and cold-welds to the previous layer as shown in figure 5.

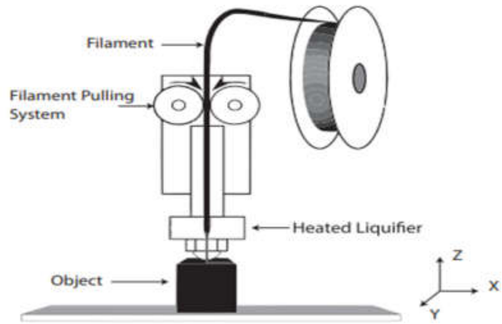

Figure 5: Fused Deposition Modeling Process [24]

4.4 Laminated Object Manufacturing

Laminated Object Manufacturing (LOM) involves layer-by-layer lamination of paper material sheets using a CO2 laser; each sheet represents one cross-sectional layer of the CAD model of the part. In this method, individual sheets are rolled onto the build platform, the binder is laid down on the sheet, and another sheet is then rolled onto the binder, fusing the two layers. A laser then cuts the cross-sectional outline of the part. Only one layer in thickness into laminated sheets. In successive layers, the process is then repeated. The excess material supports the part during the process and removed during post-processing [25]. A typical system of Laminated Object Manufacturing has been shown in figure 6.

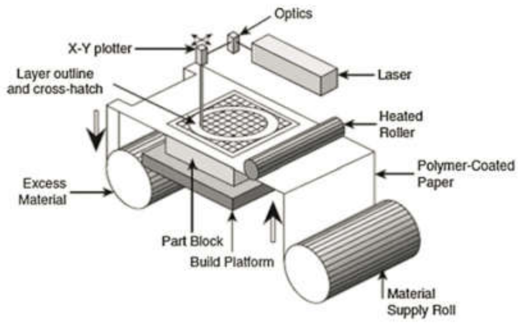

Figure 6: Laminated Object Manufacturing [26]

In addition to the slice, unwanted material is also hatched in rectangles to enable its subsequent removal but remains to act as supports during manufacturing. Once the slice is completed platform can be lowered, and material roll can be advanced by winding this excess onto a second roller until a fresh area of the sheet lies over the part. They are sealed with urethane lacquer, silicone fluid or epoxy resin after completion of the part to avoid the paper prototype from being distorted later by water absorption. The figure shows that the slices are cut in required contour from a roll of material by using a CO2 laser beam of 25-50 watt.

5. APPLICATIONS

RP technology can enhance and improve the product development process even at the same time; it helps in reducing costs due to lower processing times and quick response to design changes. Although poor surface finishes, limited strength and accuracy can be considered as some of the limitations of RP products; it can handle any degree of geometrical complexity of a given part. Since its advent, RP techniques have been extensively applied in various engineering, industrial and domestic fields to fabricate required parts and specified use. In the following Section, we categorically review some of these pertinent applications.

5.1 Aerospace industry

Among the space technology applications, NASA's human-supporting rover, which has a pressurized cabin to support astronauts, includes about 70 FDM parts. This includes housings, vents and fixtures made of acrylonitrile butadiene styrene (ABS), polycarbonate/ acrylonitrile butadiene styrene (PC/ABS) and polycarbonate materials [27].

In another application, the thermal isolating service tube for gas turbines can be suitably fabricated by RP technique. In particular, direct metal laser fusion (DMLF) may be used to produce the multi-walled unitary tube. DMLF is a commercially available laser-based RP and tooling process by which complex parts may be directly produced by melting and solidification of metal powder into successive layers of large structures; each layer corresponds to a cross-sectional layer of the 3D component [28].

Aerospace is a big deal for Concept Laser. A recent development is the additive manufacture of a bracket connector for the Airbus A350 XWB. This was made previously as a milled part of aluminium and now as a printed part made of titanium. The bracket represents a weight reduction of greater than 30%. In aerospace weight reduction is particularly important for retaining elements such as brackets [29].

5.2 Automotive Industry

Kia et al. [30] patented methods for manufacturing shell structure and sectioning panels by additive manufacturing of a unibody vehicle. Many Companies in automobiles such as General Electric Co., Ford Motor Co. and Mattel Inc. are pushing 3D printing more into the mainstream than most people realise. Ford engineers are using 3DP technology to analyse and Construct better axles of the rear truck. In future, consumers may one day be able to use 3D technology to print replacement parts when things break without going to service centres.

R. Lachmayer et al. [31] used high-speed milling and selective laser melting to build the reflector system for an automotive front lighting system. In particular, optical reflectors were manufactured, and surface roughness and reflectance were also monitored for the quality purpose.

Figure 7: Cabin bracket for the Airbus A350 XWB [29]

5.3 Biomedical Industry

3D bio-printing is a flexible manufacturing system for the fabrication of complex human organs and tissues. This section discusses the development of 3D bio-printing and its potential in medical applications.

5.3.1 Skull Reconstruction

In 1994 the Mankovich et al. [32] firstly applied 3D technology for skull reconstruction. The ideal curvature of the skull should be studied in advance because the bone is so rigid that bending is quite difficult and unsafe. Experience has shown that physical prototype models are very helpful in recognizing the ideal donor site. Skull reconstruction should be done with a split calvarial bone grafting technique [33], and the donor area is determined in advance to match the recipient calvarial bone curvature. Titanium is the realistic material for human body use. Thus, once the recently developed 3D technology starts to provide 3D titanium-based implants, they could be used in the human body. The implants can fit very well onto former defects such as calvarium or maxillary defects. Calvarial bone reconstruction would be the most revolutionary use of RP models.

5.3.2 Facial Bone Fractures

In literature, 3D printing has been used to manage multiple facial bone fractures and handling orbital wall fractures. RP techniques can suitably handle the difficulties of ideal reconstruction of the orbital wall in the correct plane. Using titanium mesh implants, we can avoid malpositioning of implant material. A mirroring tool of CAD/CAM technique is generally used to fabricate Medpore or titanium mesh taking contralateral orbit as reference [32].

Though, many facial bone ruptures can be managed with 3D printing technology; there are limited surgical fields during surgery of orbital wall fractures, which often cause reconstruction in the wrong plane. These types of problems can be overcome by using 3D printed titanium mesh implants or by preventing the malpositioning of implant material. Medpore or titanium mesh based on the RP model manufactured from the mirroring technique of CAD/CAM.

The 3D printed implant is so hard that it is not easy to cut or bend, planning and surgery should be identical, and efforts should be made to ensure that the preoperative planning and intraoperative deformities are in arrangement [32].

5.3.3 Mandibular Reconstruction

Mandibular reconstruction is mostly being performed using fibular osteocutaneous free flaps. Though the curvature of the mandible can be rebuilt using the conventional method, the 3D CAD/CAM technology can provide a more precise rebuilding modality that includes fibular osteotomy and fixation guides. Additionally, the 3D made titanium fixation plates were recently tried and are very useful for the ideal reconstruction of the mandible [32].

5.3.4. Human Skin

Lee et al. have presented preliminary studies on human skin fabrication using 3D bioprinting technology, optimise and facilitate the fabrication of a human skin model, which is more complex to incorporate secondary and adnexal structures. Such models lead to significant advancements in the understanding of the human skin as an organ, enabling the engineering of superior wound grafts as well as topical and transdermal formulation development tools to reduce the dependency on animal models [34].

5.3.5 Tissue Engineering

Tissue engineering scaffolds by 3D plotting of the alginate/methylcellulose blend can be used for simple and inexpensive tissue substitutes for regenerative therapy. [35].

Several hard tissues can be made-up with bionic materials by 3D printer. With advanced equipment and formulation protocols, some tissues containing vessels can now be fabricated [36]. With high resolution, 3D printing could be used to print scaffolds that mimic in vivo structure and environment of tissues, and there are many reports that scaffolds from 3D printing have been used in drug delivery, tissue engineering and cell viability tests [37]. An integrative computational design, manufacturing and experimental approach were used for tissue scaffold applications using 3D printing for RP to measure general mechanical characteristics of lattice to configure biomedical devices such as spinal cages [38]. From the manufacturing of medical devices and creating customized implants and prostheses used in surgical planning and education, RP can also be used to enhance the delivery of medical applications and healthcare.

Some other prominent applications in the biomedical industry include fabrication of artificial ears and nose; heart valves, cartilages, tooth and periodontal regeneration parts.

5.4 Electronic Industry

3D techniques of additive manufacturing include making electronic components like resistors, inductors and capacitors as well as printed circuits and passive wireless sensors. Design, fabrication and characterisation processes for 3D-printed microelectronics components and the circuit board by the combination of 3D printing and liquid metal paste filling techniques developed. These components include various resistors, inductors, and capacitors, and circuits include inductor-capacitor

(LC)-resonant tanks. As an example, a 3D "smart cap" with embedded LC tank as the passive wireless sensor constructed for the application of monitoring the quality of liquid food (e.g., milk and juice). In this application, The positive 3D printing devices with embedded metallic components can be used to make passive wireless sensors that benefit from 3D structures with embedded metallic conductors [39]. This letter presents one of the first examples of the exploitation of 3D printing in the fabrication of microwave components and antennas. A flexible filament, based on NinjaFlex, has been adopted for manufacturing the substrate of a 3D printed patch antenna. Subsequently, a square patch antenna is prototyped through 3D printing and measured to validate the manufacturing technology. This letter has presented the implementation of a patch antenna on NinjaFlex substrate, a new commercially available flexible material for 3D printing [40].

5.5. Textile Industry

Besides efforts to create textile-shaped structures by 3D printing [41], fibrous materials [42] and net-like textile structures [43] inserted in 3D printed forms. Recently a more systematic study was published, investigating the adhesion of ABS, polylactic acid (PLA), and other types of synthetic and human-made woven and knitted fabrics [44]. Here, however, the distance between the printing nozzle and textile surface as an important factor defining the adhesion between textile and 3D printed parts was not taken into account.

5.6 Miscellaneous Applications

The use of RP technology in jewellery and bead design and manufacture offers a significant revolution in this industry. The jewellery industry has traditionally been regarded as one which is the heavily craft-based industry. Automation is usually limited to the use of machines in various individual stages of jewellery and Bead manufacturing [45].

Similar to the jewellery industry, the mint or coin sector has traditionally been considered to be highly labour-intensive and craft-based. It depends mainly on qualified craftsmen's abilities to generate "embossed" or relief designs on coins and other associated products. The use of RP technology is increasing in this industry at a fast pace [46].

In another application of RP technology, the tableware industry is worth mentioning. CAD and RP technologies are used as an integrated system to create better designs in a faster and more accurate manner. The general methodology used in the tableware industry is similar to that used in the coin and jewellery industries. New computer tools with special programs developed to adapt decorative patterns to different variations of size and shape of tableware are needed for this particular industry. Also, a method for generating motifs along a circular arc can be developed to supplement the capability of such a system [47]. As another domestic application, the furniture design industry is also growing at a rapid pace looking at the increased need for urban smart furniture in cities these days [48].

6. CONCLUSIONS

RP is, undoubtedly, one of the fastest growing new technologies for manufacturing the various products of industrial and domestic use. It operates by adding or depositing the material in the layer by layer and governed by a 3D CAD model usually connected with the automated machine. This paper highlights the various RP techniques and also focuses on their important and recent applications. It provides a platform for new learners, researchers as well as RP practitioners to compare and contrast the latest trends and applications in this area. The difficulties associated with one technique while creating the complicated and different contours in a product can be suitably handled by adopting other RP technique. The paper mainly brings a fruitful review of RP applications and process parameters which may motivate related researchers to combine useful features of them to develop efficient RP systems. It may also steer an insight into the challenges and bottlenecks of different versions of RP. Finally, it summaries that one should justify the use of particular RP technique based on product application, commercial viability, budget availability and on the possibility of controlling different process parameters involved in the system.

.

REFERENCES

[16] K. Cooper, Rapid prototyping technology: selection and application, Marcel Dekker, New York,CRC press, 2001.

[17] X. Yan and P. Gu, "A review of rapid prototyping technologies and systems" Computer-aided design (1996), volume 28, no. 4, Pages 307-318.

[18] S. Ashley, "Rapid prototyping is coming of age" Mechanical Engineering (1995) volume 117, no. 7, Page 62.

[19] A. K. Matta, D. R. Raju, and K. N. S. Suman, "The integration of CAD/CAM and rapid prototyping in product development: a review" Materials Today: Proceedings (2015), volume 2, no. 4-5, Pages 3438-3445.

[20] W. Wang, J. G. Conley, and H. W. Stoll, "Rapid tooling for sand casting using laminated object manufacturing process" Rapid Prototyping Journal (1999) volume 5, no. 3, Pages 134-141.

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

[22] T. Rayna and L. Striukova, "From rapid prototyping to home fabrication: How 3D printing is changing business model innovation" Technological Forecasting and Social Change (2016) volume 102, Pages 214-224.

[23] Jung S. Kim, S. W. Lee P.H. Lee, "Fabrication of aramid-filled composite using stereolithography apparatus (SLA) process" (2018), Page 25.

[24] A. Kochan, "Features Rapid prototyping wins widespread acceptance" Assembly Automation (1997) volume 17, no. 3, Pages 218-221.

[25] Wohlers Associates, Wohlers Report 2018, "https://wohlersassociates.com/press74.html" March, 2018.

[26] C. K. Chua, K. F. Leong, and C. S. Lim, RP: Principles and Applications in Manufacturing.: World Scientific, (2003).

[27] C. C. Kai, "Three-dimensional rapid prototyping technologiesand key development areas" Computing and Control Engineering Journal (1994) volume 5, no. 4, Pages 200-206.

[28] D. Kochan, "Solid freeform manufacturing- possibilities and restrictions" Computers in Industry (1992), volume 20, no. 2, Pages 133-140.

[29] A. Ahmad, S. Darmoul, W. Ameen, M. H. Abidi, and A. M. Al-Ahmari, "Rapid prototyping for assembly training and validation" IFAC-Papers OnLine (2015), volume 48, no. 3, Pages 412–417.

[30] Jinghon Li, "Improving stereolithography parts quality-Practical solutions" Proceedings of the Third International Conference on Rapid Prototyping (1992), Pages 171-179.

[31] J. Cohen and S. A. Reyes, "Creation of a 3D printed temporal bone model from clinical CT data" American journal of otolaryngology (2015), volume 36, no. 5, Pages 619-624.

[32] B. Basu, Fundamentals of Scaffolds Fabrication Using Low Temperature Additive Manufacturing. Singapore: Springer (2017).

[33] S. Yu, "Slicing Algorithm of VRML Model in Rapid Prototyping," Journal of Modeling and Optimization, (2015) volume 7, no. 1, Pages 45-49.

[34] M. Hamoud, A. I. EL-Wahab, and A. Barakat, "Speeding up algorithm for building the STL model 3D printing" International Conference on Applied Mechanics and Mechanical Engineering (2016), Pages 19-21.

[35] X. F. Liu, S. N. Al Sunny, M. R. Shahriar, M. C. Leu, M. Cheng, and L. Hu, "Implementation of MTConnect for Open Source 3D Printers in Cyber Physical Manufacturing Cloud" ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers (2016), Pages V01AT02A019-V01AT02A019.

[36] C. M. Madla, S. J. Trenfield, A. Goyanes, S. Gaisford and A. W. Basit, "3D printing technologies, implementation and regulation: An overview" 3D Printing of Pharmaceuticals (2018), Springer, Cham, Pages 21-40.

[37] C. M. Felipe, D. Patrocinio, J. M. Laza, L. R. Rubio, and J. L. Vilas, "Evaluation of postcuring process on the thermal and mechanical properties of the Clear02™ resin used in stereolithography" Polymer Testing (2018), volume 72, Pages 115-121.

[38] G. H. Wu and S. H. Hsu, "Polymeric-based 3D printing for tissue engineering" Journal of medical and biological engineering (2015), volume 35, no. 3, Pages 285-292.

[39] O.S. Carneiro, A.F. Silva, and R. Gomes, "Fused deposition modeling with polypropylene," Materials and Design (2015), volume 83, Pages 768–776.

[40] B. Bhushan and M. Caspers, "An overview of additive manufacturing (3D printing) for microfabrication," Microsystem Technologies (2017), volume 23, no. 4, Pages 1117–1124.

[41] I. Gibson, D. Rosen, and B. Stucker, Additive manufacturing technologies, volume 17, Springer, New York (2014).

[42] C. Chapman, 3D Printing a space vehicle, Stratasys, https://www.stratysys.com/resources/search/case-studies/nasa, April, 2019.

[43] E. Zurmehly, C. Frost, M. O'brien, and D. G. Godfrey, U.S. Patent No. 9,644,495, (2017).

[44] L. Nickels, "AM and aerospace: an ideal combination" Metal Powder Report (2015), volume 70, no. 6, Pages 300-303.

[45] H. G. Kia, N. Huang, J. P. Spicer, and J. F. Arinez, U.S. Patent Application No. 10/022,912, (2018).

[46] R. Lachmayer, G. Kloppenburg, and A. G. Wolf, "Rapid prototyping of reflectors for vehicle lighting using laser activated remote phosphor" Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XIX (2015), volume 9383.

[47] J. W. Choi and N. Kim, "Clinical application of three-dimensional printing technology in craniofacial plastic surgery" Archives of Plastic Surgery (2015), volume 42, no. 3, Pages 267-277.

[48] [33] H. J. Lee, J. W. Choi, and I. W. Chung, "Secondary Skull Reconstruction With Autogenous Split Calvarial Bone Grafts Versus Nonautogenous Materials" Journal of Craniofacial Surgery, (2014) volume 25, no. 4, Pages 1337-1340.

[49] V. Lee, G. Singh, J. P. Trasatti, C. Bjornsson, X. Xu, T. N. Tran, S. S. Yoo, G. Dai, and P. Karande, "Design and fabrication of human skin by three-dimensional bioprinting" Tissue Engineering Part C: Methods (2014), volume 20, no. 6, Pages 473-484.

[50] K. Schütz, A. M. Placht, B. Paul, S. Brüggemeie, M. Gelinsky, and A. Lode, "Three-dimensional plotting of a cell-laden alginate/methylcellulose blend: towards biofabrication of tissue engineering constructs with clinically relevant dimensions" Journal of tissue engineering and regenerative medicine (2017), volume 11, no. 5, Pages 1574-1587.

[51] Q. Gu, J. Hao, Y. Lu, L. Wang, G. G. Wallace, and Q. Zhou, "Three-dimensional bio-printing" Science China Life Sciences (2015), volume 58, no. 5, Pages 411-419.

[52] K. Jakab, C. Norotte, F. Marga, K. Murphy, G. Vunjak-Novakovic, and G. Forgacs, "Tissue engineering by self-assembly and bio-printing of living cells" Biofabrication, (2010) volume 2, no. 2, Pages 1-14.

[53] P. F. Egan, I. Bauer, K. Shea, and S. J. Ferguson, "Integrative design, build, test approach for biomedical devices with lattice structures," ASME Paper No. DETC2018-85355, 2018.

[54] S. Y. Wu, C. Yang, W. Hsu, and L. Lin, "3D-printed microelectronics for integrated circuitry and passive wireless sensors," Microsystems and Nanoengineering (2015), 1, page 15013.

[55] S. Moscato, R. Bahr, T. Le, M. Pasian, M.; Bozzi, L. Perregrini, M. M. Tentzeris, "Infill-dependent 3-D-printed material based on NinjaFlex filament for antenna applications" IEEE Antennas and Wireless Propagation Letters (2016), volume 15, Pages 1506-1509.

[56] R. Melnikova, A. Ehrmann, and K. Finsterbusch, "3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials" IOP conference series: materials science and engineering, (2014) volume 62, No. 1, Pages 1-6.

[57] C. Richter, S. Schmülling, A. Ehrmann, and K. Finsterbusch, "FDM printing of 3D forms with embedded fibrous materials" Design, Manufacturing and Mechatronics: Proceedings of the 2015 International Conference on Design, Manufacturing and Mechatronics (ICDMM2015) (2016), Pages 961-969.

[58] L. Sabantina, F. Kinzel, A. Ehrmann, and K. Finsterbusch, "Combining 3D printed forms with textile structures mechanical and geometrical properties of multi-material systems" IOP Conference Series: Materials Science and Engineering (2015), volume 87, no. 1, Pages 1-5.

[59] E. Pei, J. Shen, and J. Watling, "Direct 3D printing of polymers onto textiles: experimental studies and applications" Rapid Prototyping Journal (2015), volume 21, no. 5, Pages 556-571.

[60] C. Starrett, M. Doman, C. Garrison, and M. Sleigh, "Computational bead design: A pilot summer camp in computer aided design and 3D printing for middle school girls" Proceedings of the 46th ACM Technical Symposium on Computer Science Education, ACM (2015), Pages 587-590.

[61] C. C. Kai, R. K. L. Gay, S. K. F. Cheong, L. L. Chong, and H. B. Lee, "Coin manufacturing using CAD/CAM, CNC and rapid prototyping technologies" International Journal of Computer Applications in Technology (1995), volume 8, no. 5-6, Pages 344-354.

[62] C. K. Chua, R. Gay, and W. Hoheisel, "Computer Aided Decoration of Ceramic Tableware. Part I: 3-D decoration" Computers and Graphics (1997), volume 21, no. 5, Pages 641-653.

[63] A. Rinaldi, M. Caon, O. A. Khaled, and E. Mugellini, "Designing urban smart furniture for facilitating migrants' integration: the co-design workshop as approach for supporting inclusive design" Congress of the International Ergonomics Association, Springer, Cham, (2018) , Pages 461–470.