Material issues in additive manufacturing: A review

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Review

Material issues in additive manufacturing: A review

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ABSTRACT

Today, *Additive manufacturing* (AM) is a well known technology for making real three dimensional object, with metal or ceramic or plastic or thereby combination, which may be subjected to various applications. *Additive bio-manufacturing* (ABM) techniques are highly in demand and researches have been going on for making these safer and more versatile. For more utilization and versatility, special attention is required to develop new materials which can help in increasing the service life, bioactivity, cell growth along with the desired mechanical properties. The present paper aims to review some of the most widely used AM techniques for biomedical applications. Special attention has been paid on *Fused deposition modeling* (FDM) based AM technique as it is economical, environmentally friendly and adaptable to flexible filament material. This review paper will be helpful to the researchers, scientists, manufacturers, etc., working in the field of ABM.

Contents

1. Introduction

AM is one of the most widely used technique for constructing prototypes with higher dimensional accuracy and much less time. In today's scenario, modern industries are liable to implementing several AM techniques such as: *Stereo-lithography* (SLA), *Selective laser sintering* (SLS), *Laminated object manufacturing* (LOM), *Fused deposition modeling* (FDM), *Direct metal laser sintering* (DMLS), *3D printing* (3DP), etc. Basically, all these AM techniques employ the same basic principle wherein the final component is fabricated with layer by layer addition of the material. A brief schematic for fabricating implant in medicine is shown in Fig. 1, while Fig. 2 describes a detailed classification of various types of ABM techniques.

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Table 1
Commercial AM techniques, their manufacturer(s) and material provider(s).

Name	Manufacturer(s)	Material provider(s)
SLS, selective heat sintering	3DSYSTEMS, Farsoon Technologies, Blueprinter (Denmark), eos, MC Machinary Systems, Wuhan Binhu Mechanical & Electrical Co., Ltd.	3DSYSTEMS, Paramount Product Development Specialists, Farsoon Technologies, Concept Laser, eos, LuxExcel, Wuhan Binhu Mechanical & Electrical Co., Ltd.
Selective laser melting	MICROFABRICA, REALIZER, SLM Solutions, Wuhan Binhu Mechanical & Electrical Co., Ltd.	MICROFABRICA, REALIZER, SLM Solutions, Wuhan Binhu Mechanical & Electrical Co., Ltd.
Metal laser melting	Concept Laser	Concept Laser
EBM	Arcam (Sweedon), Sciaky	Arcam (Sweedon), Sciaky
Laser metal deposition	BEAM (France)	BEAM (France)
Inkjet, poly jet, binder jet	Envisiontec, ExOne, MicroFab, Stratasys, Solidscape	Envisiontec, ExOne, MicroFab, Prodways, Stratasys, Solidscape
SLA, lithography-based ceramic manufacturing	3DSYSTEMS, CMET Inc., Somos, Lithoz, Prodways, Wuhan Binhu Mechanical & Electrical Co., Ltd.	3DSYSTEMS, CMET Inc., Somos, Lithoz, Prodways, Wuhan Binhu Mechanical & Electrical Co., Ltd.
Digital wax machine	DWS	DWS
FDM	UP-3D, Stratasys, CandyFab, Fab@Home, MAKERBOT, Solidscape, Polyflex	UP-3D, Stratasys, CandyFab, Fab@Home, MAKERBOT, LuxExcel, RepRap, Solidscape, Argyle Materials Inc., Polymakers®
DMLS	Insstek	Concept Laser, Insstek
Metal powder bed fusion	Renishaw	Renishaw
Ultrasonic additive manufacturing	Fabrisonic	Fabrisonic
LENS	Optomec	Optomec, Concept Laser
LOM	Cubic Technologies	Cubic Technologies
3DP	Asiga, Keyence Corporation	Asiga, Keyence Corporation
ZCast	ZCast	ZCast

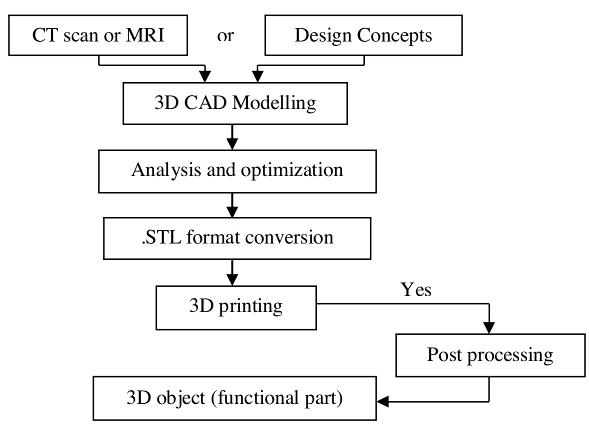

Fig. 1. Schematic of implant fabrication, [142].

AM has a strong share market in medical and dental industry and it is the 3rd largest sector [1]. The new era of AM enables the designer to simulate the implant design prior to their manufacturing. AM techniques cut the cost and time of implant manufacturing. The ability of AM technology to produce actual functioning parts is also a contributing factor to its newly acquired popularity [2]. Generally in medicine, AM usually work integrated with digital imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI). The data collected from CT or MRI scans (in Ducom format) is converted into a 3D bio-model with the help of Mimics or 3D-doctor like computer software. Further, the 3D bio-model is converted to *Standard Triangulation Language* (.STL) file format and imported into an AM setup, [147]. Till date, numerous medical applications have been fabricated with available AM which includes: soft scaffold, human osteosarcoma, blood vessels, cartilage, hip joint, knee joint, bone, soft tissues, etc. [3,4,5]. Currently, a number of vendors are available for a single AM technique and for their materials too. Table 1 shows the manufacturer(s) of various types of AM techniques and their recognized materials provider(s).

2. Materials for AM

A variety of materials are used for AM applications and the research for further development of new materials is in progress. Today, various categories of biomedical materials are available with us in-terms of metals, alloys, ceramics, bioactive glass, plastics

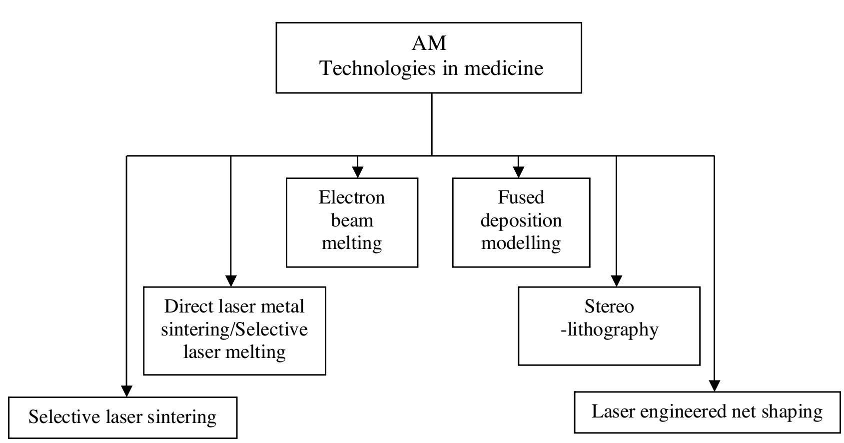

Fig. 2. Classification of various types of AM techniques in medicine.

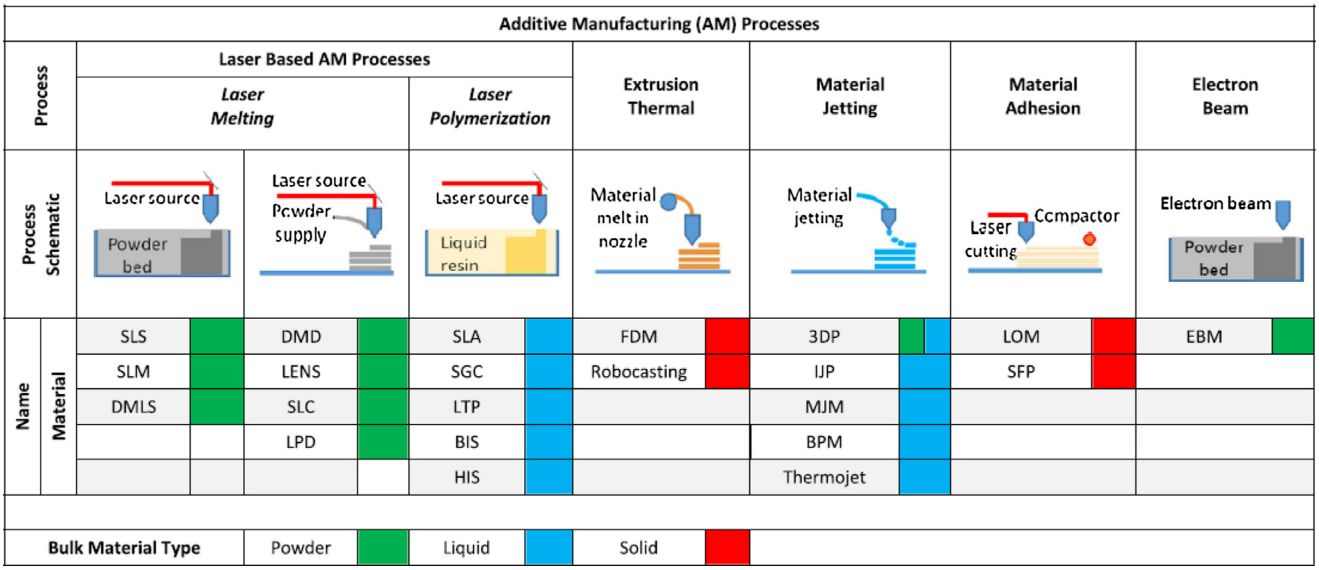

Fig. 3. Materials category for AM technologies [143].

Table 2
Biomedical materials, [146].

Implant material	Abbreviation/notation	Application
Ti and Ti alloys	CP–Ti	Bone fixation
	Ti–6A1–4V	Artificial valve, stent, bone fixation
	Ti–6Al–7Nb	Dental application, knee joint, hip joint
	Ti–5Al–2.5Fe	Spinal implant
	Ti–15 Zr–4Nb–2Ta–0.2Pd	Dental applications
	Ti–29Nb–13Ta–4.6Zr	Dental applications
	83%–87%Ti–13%–17%Zr (Roxolid)	Dental application
Stainless steel	316L	Dental, knee joint, hip joint, surgical tools
Cobalt chromium alloy	Co–Cr–Mo, Co–Ni–Cr–Mo	Artificial valve, bone fixation, dental applications, knee joint, hip joint
Shape memory alloy	NiTi	Catheters, stents
Polymers	PMMA, PE, PEEK	Dental applications, articular cartilage, hip joint bearing surface, knee joint bearing surface, soft tissues
Bio-glass	$SiO_2/CaO/Na_2O/P_2O_5$	Dental applications, orthopaedic implants
Zirconia	Zirconia	Porous implants, dental applications
Alumina	Al_2O_3	Dental applications
Hydroxyapatite	$Ca_5(PO_4)_3(OH)$	Dental applications, implant coating material

and their combinations. Fig. 3 illustrates the category of material allotted to various AM techniques. Metals have been used for implant manufacturing since more than 120 years ago [6]. During early development, corrosion and insufficient strength problems were faced, however, after the introduction of the stainless steel (SS) in 1920, superior corrosion resistance properties attracted clinical interest. In the recent past, along with SS-316L, Ti and Co–Cr–Mo alloys, various polymers, glass and ceramic materials found their applications as an implant material [7,8]. Table 2 summarizes different type of biomedical material. It is a well established assumption that the mechanical properties of selected implant material must fulfill its functions such as providing support, fixation and bone replacement. Further, it should possess an inertness and corrosion resistance properties in the body so that its implantation should not cause any harm to body [9]. Post treatment and processing techniques plays a vital role in required implant properties [10].

Commercially pure Ti, Ti alloys, surgical grade stainless steel and cobalt–chromium alloys are among most widely used metallic based implant materials [11,12]. Particularly, austenitic SS-316L is the first recommended biomaterial for nails, screws, plates, etc. It has a reasonable corrosion resistance tendency due to its lower carbon content. However, there are huge chances that SS-316L may corrode inside the body under high stressed oxygen-depleted environment [13]. However, SS-316L is easy to fabricate and processes required level of mechanical and corrosion properties, as a result of which it has established as one of the most predominant implant alloy [14]. The continuous research for the development of safer material led to the invention of cobalt based alloys. Further the discovery of Ti, and specifically Ti–6Al–4V, has become one of the most commonly used materials for biomedical applications. Ti–6Al–4V alloy offers most desirable medical characteristics which include: corrosion resistance, bio-compatibility, shear strength, good elastic modulus, density and osteointegration [15]. All aforesaid materials are printable with existing AM equipments such as: SLS, DMLS, LENS, EBM, etc.

Ceramic such as alumina (Al_2O_3), zircon dioxide (ZrO_2), hydroxyapatite (HAp or Ca_{10} $(PO_4)_6$ $(OH)_2$), bio-glass (SiO_2–CaO–Na_2O–P_2O_5–MgO), titanium oxide (TiO_2), tri-calcium phosphate (TCP or $\alpha/\beta Ca_3$ $(PO_4)_2$), are very efficient for their tasks inside the human body. These materials are most commonly used as/in the coating material, hip joint caps, articular cartilage, etc. Current studies have been focused for searching new materials further filling the gaps in-terms of rapid healing, biocompatibility issues, poor wet-ability, etc. [16,17]. Bio-active glass is one of latest inventions which have been used extensively for clinical applications [18]. One advantage associated with bio-active glass and glass-ceramic material is their tendency to form biologically active HAp surface layer, which permits their bonding between bone and soft tissue [19]. Z-Cast is the most suitable 3D printer for fabricating ceramics based biomedical components.

Equipments like: SLA, FDM, LOM, etc., use various types of polymer materials for dental, cardiovascular, soft tissue, drug delivery, and tissue engineering and orthopedic applications. Natural polymers (cellulose, natural rubber, sutures, collagen, deoxyribonucleic acid, etc.) are known for their friendly behavior to the biological environment in which these are used. These are generally an extracellular matrix of connective tissue like: tendons, ligaments, skin, blood vessel, and bone [20]. Also, these materials are degradable and are more environmental friendly. On the other side synthetic polymers (which include poly-ethylene (PE), poly-propylene (PP), poly-ethylene-terephthalate (PET), poly-vinyl-chloride (PVC), poly-ethylene-glycol (PEG), poly-caprolactone (PCL), poly-tetra-floroethylene (PTFE), poly-glycolide (PGA), poly(lactide-*co*-glycolide) (PLGA), Ultra high molecular weight poly-ethylene (UHMWPE), Poly(lacticacid) (PLA), Poly(ethylene terephthalate), poly-etheretherketone (PEEK), poly-methyl-methacrylate (PMMA), nylon and others) are also used for biomedical applications and offer superior properties comparative to natural polymers.

Apart from the wide availability of AM techniques and their processing materials, still most of biomedical implants/devices demands post treatment in order to improve the surface characteristics of the fabricated part. This highlights some weak pools of existing AM techniques or their materials or of both. Generally, pure materials are employed for most of the AM techniques due to which the properties possessed by the resulting components are sometimes unsuitable for different end user applications. Advance materials (such as composites) could be developed for various ABM techniques in a way to eliminate the time and cost incurred during their post treatments. Cost of metal powders, limited number of varieties and controlled by the AM machine manufacturers, safety issues (lasers in the case of metal powders based AM), shrinkage of the parts, poor surface finishes and multi-behavioral components (for e.g. Combinations of both magnetic and non-magnetic) are some of the major requirements in today's manufacturing sector. In order to achieve such characteristics, one needs to develop a custom made composition of workhorse materials. In the upcoming sub-sections, we have tried to review the various techniques used for the production of metal powders, ceramics and polymer/composite feedstock filaments for various AM techniques.

2.1. Production of metal powders

SLS, LENS, EBM, DMLS, SLM, EMB, Prometal, etc., are those AM techniques which utilize metal powders for the development of functional and non-functional prototypes. Stainless steel, Co–Cr alloy, CP–Ti, Ti–6Al–4V, NiTi, Inconel, gold, silver, copper, Al and their alloys are most widely used metal powders, nowadays [21,22,23,24,25]. Since most of the commercially used AM techniques are rigid in-terms of input processing variables (even characteristics of metal powder to be used), hence it is very difficult to customize the composition according to the end user applications of resulting components. Further the commercially available metal powders are often supplied by the additive manufacturers, which cost very high. Problems like: surface roughness, damage tolerance, inferior fatigue & tensile strength, sensitively affected by subtle changes to the chemistry and microstructure are also highlighted in the literature [26]. Till date, numerous research efforts have been made to developed in-house metal powders in order to suit best the required applications and being economical simultaneously [27,28,29]. Plasma rotating electrode process, gas atomization, plasma atomization, electrolytic processing, high-pressure water atomization and mechanical crushing are some of the commercially established processes (for a detailed list, refer Fig. 4) for the production of metal powders [30,31,32,33,25,34].

Each of the above mentioned routes has integral advantages and limitations. The plasma rotating electrode process is known for producing high purity metal powders, however the powder produced by this route is not fine as desired for most of applications, especially in biomedicine [30]. On the other hand, gas atomization uses air, steam or an inert gas to produce powders from molten metal and produces finer spherical powder ranging from 10 to 300 μm [35]. In gas atomization, satellite formation is difficult to avoid in which shows detrimental to achieving good flow-ability. Plasma atomization, patented by PyroGenesis and Hydro-Quebec, is used to produce highly pure spherical the powders, molybdenum, copper and Inconel with a variety of sizes [36]. This process includes an electric source which is used to supply power to a plasma torch, generates a jet of extremely hot ionized inert gas with high velocity. The high velocity of striking ions ensured atomization and extended high temperature zone to allow spheroidization. The equipment required for this technique is costly and required specially trained operators.

In an another powder production process, metal oxide ores are reduced with the help of hydrogen, carbon monoxide and dissociated ammonia gas to produce their respective metals such as: iron, cobalt, copper, tungsten and molybdenum powders on a commercial scale. However, reduction processes are time consuming and demands lots of experimental setups to get the required properties of the reduced metal powders [37].

An electrolytic process involves the deposition of a metallic element at the cathode of an electrolytic cell. The most common application is in the production of copper powder. The electrolysis conditions for the production of copper powder are electrolysis-solution temperature of 48–52 °C, sulfuric-acid concentration of 120–250 g/L. The deposited copper powder is periodically scraped from the cathode and post treated to produce copper powder [38].

Mechanical alloying is a dry and a high energy milling process for the production of fine metallic powders with controlled microstructure. This process involves the repeated welding and fracturing of a mixture of metallic and non-metallic powders in a highly activated ball mill. Under the extreme state of hydrostatic compression the brittle material undergoes fairly large amounts of plastic strain before fracture. As the process continues, the materials are fractured and re-welded by the grinding ball mill, which leads to continual refinement of the internal structure of metal powder [39,40]. This method can be used for the production of composite metallic powders. Prior to the use of in-house developed metallic powders, these must be characterized using the following techniques:

- Laser particle size distribution (PSD) measurements
- X-ray computed tomography (XCT)
- X-ray diffraction (XRD)
- Scanning electron microscopy (SEM)
- Dispersive elemental analysis (EDS)
- X-ray photo-spectroscopy (XPS)

2.2. Production of ceramic powders

Chemistry and crystal phase purity is most desired properties of ceramic synthesis techniques along with controlled particle size distributions. Different technique suits different types of ceramics. In addition to the technical advantages of various processes, advantageous production costs also influence process selection.

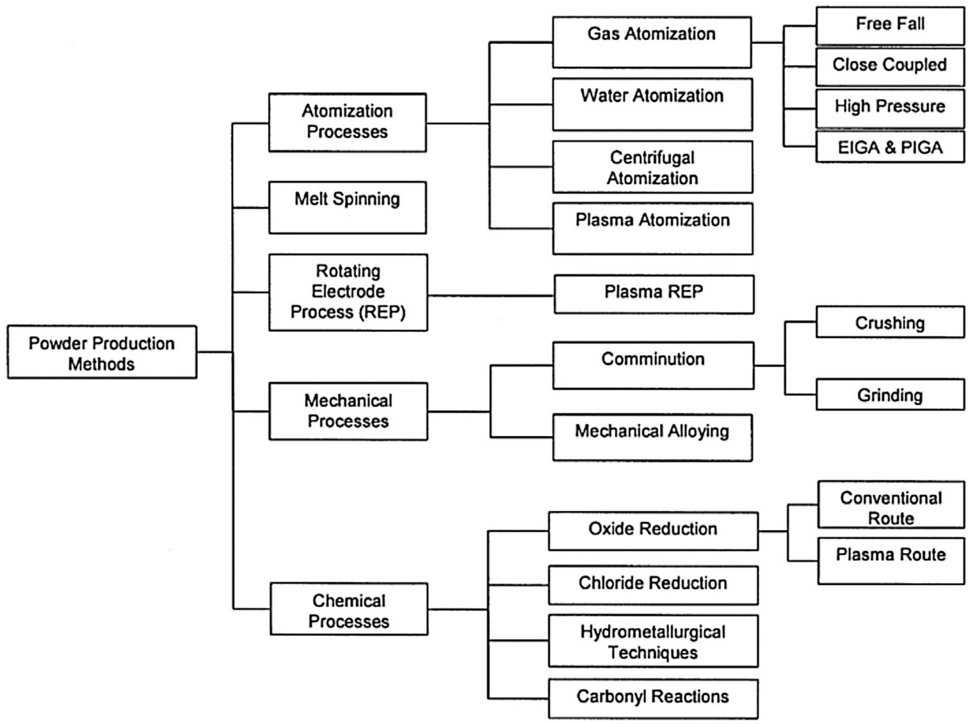

Fig. 4. Methods of powder production [37].

The production of nano-sized oxide powders are very important for the fabrication of high-performance ceramic parts through AM. The conflicting requirements for a ceramic-processing method and high demand for low cost techniques have motivated the researchers to come with innovative concepts. During the past, many groups have participated in this quest for flexible, simple, and cost-effective processing, generating a multitude of new methods [41].

Some examples of commercial ceramic powder processes include solid phase synthesis of Si_3N_4 and SiC, $A1_2O_3$ and ZrO_2, and gas synthesis of TiO_2 and SiO_2 [42]. Processing of ZrB_2 has relied upon comminution of starting powders using grinding media typically comprised of tungsten carbide, Si_3N_4, SiC, ZrO_2, or Al_2O_3 [43]. Noviyanto et al. [44] utilized a new pulverization process for the synthesis of $SrTiO_3$ single crystals, TiO_2 single crystals and $BaTiO_3$ ceramic in a gas stream containing air and ammonia at high temperature. Colombo in 2006 [45] outlined some of the methods used for the production of cellular or porous ceramics. Messing et al. [46] highlighted that a variety of spray pyrolysis techniques have been developed to directly produce ceramic powders from solutions. In their work they have studied the effect of process parameters on the controlled morphology and composition of the ceramics. A model incorporating solute diffusion in the droplet and solvent evaporation from the droplet surface was explored to establish the critical parameters leading to the solid particle formation. Similarly, Pham et al. [47] processed ZrB_2 using spark plasma sintering with the addition of B_4C in order to remove oxide impurities. Shangguan et al. [48] synthesized $Ba_{0.991}Bi_{0.006}TiO_3$@$ZnO–B_2O_3–SiO_2$ (BBT@ZBSO) nano particles and ceramics and examined the core–shell structure through energy-dispersive spectroscopy (EDS). The effects of ZBSO additive on the phase composition, microstructure, sintering temperature and dielectric properties of the BBT ceramics were studied. Similar inspection techniques, as mentioned in above sub-section, may be adopted for the characterization of synthesized ceramics.

2.3. Production of polymer/composite feedstock filaments

According to Stratasys Inc. USA white paper, there are about 11 types of FDM materials which are commercially available to satisfy most of the applications, [148]. These materials have unique properties including chemical resistance, transparency, biocompatibility, thermal resistance and strength, etc. Research at different geographic regions is in progress for the development of new thermoplastic FDM material. Development of new FDM materials based on metals and other filler materials like; aluminium oxide, aluminium, iron, copper, silicon carbide, fibers and ceramics offers a challenging task because of the specific requirement of feed stock filament, Novakova et al. [49]. Wu [50] stated that the work for the development of new metal and ceramic based material has been in progress for rapid fabrication of functional component by FDM. A similar work was carried to develop metal/polymer composite material for FDM (shown in Table 3) with an aim to direct rapid tooling using iron particle in a nylon type matrix in suitable proportion, Masood and Song [51]. Variation of the amount of various constituents required for different volume of the part materials for the 70/30% (nylon/iron) and 60/40% (nylon/iron) campsites are shown in Fig. 5(a) and (b), respectively. These figures provide guidelines for the relative amount of constituent materials required for a given volume of parts to be fabricated on the FDM system. However, Bigg [52], Nikzad et al. [53] worked on the development of new metal, polymer composite consisting of an FDM-grade ABS containing 10% fine iron particles by volume was experimentally investigated and a mixture of 10% iron powder and 90% ABS powder by volume was prepared in screw extruder machine found higher values of mechanical test. Fig. 6(a) shows metal/polymer based FDM feedstock filament and Fig. 6(b) shows test sample produced on FDM3000 from new Iron/ABS composite (black color) and unfilled ABS (white color).

Thrimurthulu et al. [54] presented an approach that determined the optimal part deposition orientation for FDM process by considering two contradicting objectives, namely build time and average part surface roughness, and were minimized by minimizing their

Table 3
Constituents of new iron/polymer composites.

Sample no.	Iron particle size (μm)	By volume (%)		By weight (%)		Surfactant/plasticiser
		Nylon	Iron	Nylon	Iron	
1	50–80 (coarse)	70	30	23.10	70.91	6
2	50–80 (coarse)	60	40	15.95	76.15	7.9
3	<30 (fine)	60	40	15.95	76.15	7.9

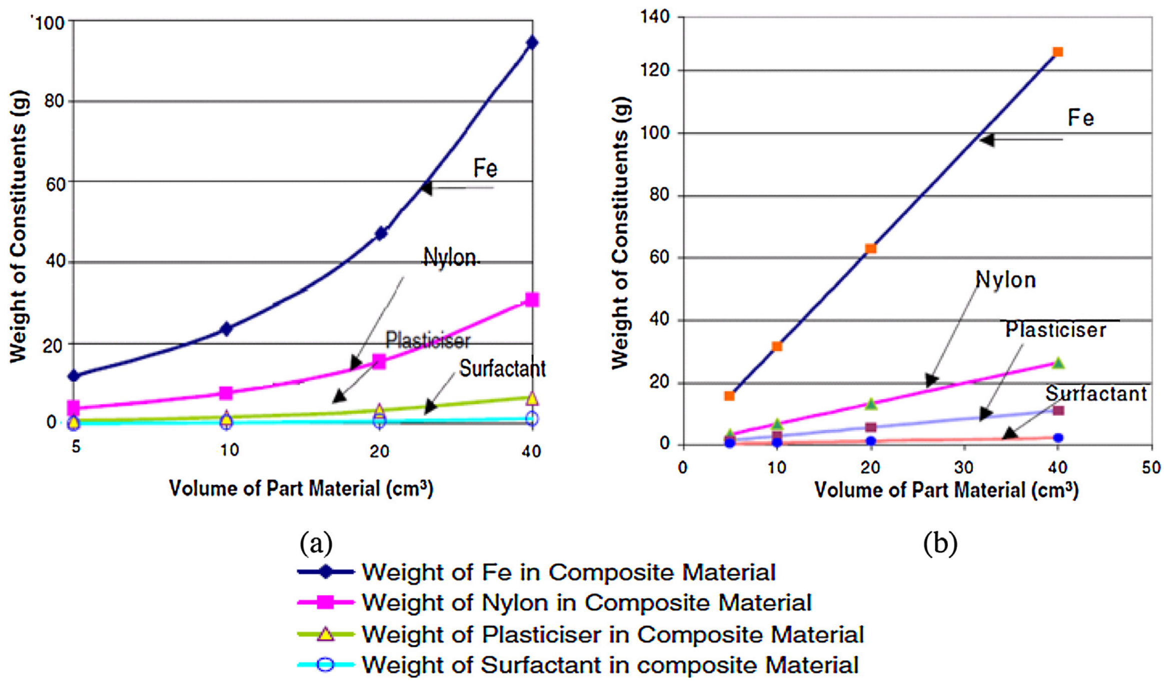

Fig. 5. Relative constituent elements as a function of volume of part material [51].

Fig. 6. Developed wire with specimens.

weighted sum. Nikzad et al. [55] investigated the thermal and mechanical properties of metal-particle filled ABS composites for FDM application where a test sample made of Iron/ABS and Copper/ABS were mixed by centrifugal grinder were extruded in screw extruder machine both filled and unfilled ABS wire were tested for its elongation. The use of RP technology for RT and RM has given rise to the development of application oriented composites [56]. The FDM is capable of yielding strong composite parts as bond forms between successive roads and layers due to partial and full melting of composite feedstock filaments [149]. Work has been in progress in some universities and research institutions to develop new metallic and ceramic materials for rapid fabrication of functional components by FDM with higher mechanical, thermal and wear resistant properties [57].

There are many obstacles in the development of FDM feedstock wire like; composition having relative melt flow index, uniform distribution of filler in plastic and extrusion of continuous wire, etc. Venkataraman [58] highlighted the main obstacle for application of new materials with specific characteristics was often come from use of intermediate precursors such as a filament and problems were encountered during preparation of new feedstock filament due to use of precursor filament. Reddy et al. [59] developed principle of polymer extrusion called extruder deposition process (EDP) which deposited material on a computer-controlled positioning system to build components. Effect of variable like; nozzle temperature, chamber temperature and road gap was studied as their influence on bond strength and surface finish. The various materials such as: wax, paper, nylon, glass filled nylon, metal filled nylon, metal filled ABS and ceramics have been reported by various researchers [60]. Rutgers University in the United States has carried out considerable work in the development of fused deposition of ceramics (FDC) and metals. They have fabricated functional components of a variety of ceramic and metallic materials such as silicon nitrate, PZT, aluminum oxide, hydroxyapatite and stainless steel for a variety of structural, electro-ceramic and bio-ceramic applications [57].

Researchers at Virginia Tech have developed a new high performance thermoplastic composite for FDM, involving thermotropic liquid crystalline polymers (TLCP) fibers and have used it in the FDM system to fabricate prototype parts. The tensile modulus and strength of this material were approximately four times those of ABS [61]. The feedstock filament for FDM was prepared with the mixture of polypropylene and ceramic powder such as mullite (Al_2O_3, $2SiO_2$), fused silica (SiO_2), titanium dioxide (TiO_2) and alumina (Al_2O_3).

The various additives such as tackifier, elastomers, plasticizer and wax are added to control the various properties such as flexibility, stiffness, viscosity and strength of the filament [62]. The use of poly lactic acid (PLA) and tri calcium phosphate (TCP) as resorbed composite was state of the art in tissue engineering and maxillofacial surgery. The general suitability of PLA for the processing with FDM was evaluated and material specific effects (for example crystallization and shrinkage) were observed and the characterization of the semi-crystalline biodegradable material by thermal, mechanical and microscopic analysis was carried out. Components of PLA/TCP have sufficient mechanical properties for their potential use as a scaffold was obtained [63]. A new polymer nano-composite material which is a mixture of polycaprolactum (PCL), montmorillonite (MMT) and hydroxyapatite (HA) as a filler can be used as an alternative material for FDM. PCL is bioresorbable, more stable in ambient condition, less expensive and easily available as compared to PLA [64]. For FDM applications biomaterials such as PCL [65,66,67], HA [68], PP-β-TCP [69], POT/PBT, PCL-β-TCP [67], β-TCP [70] are reported by many researchers. Various medical grade materials are also available, which can be used to fabricate RP models on the basis of their use in different medical applications [71]. Marwah et al. [72] used biomass (oil palm) for the development of FDM filament. Prototypes produced using advanced or composite filament possesses enhanced mechanical properties as compared to commercial material. These prototypes can be used as rapid tooling applications like; dentistry tools, inserts and automotive parts to appreciable service life. Nowadays, wide varieties of materials are available for FDM process which extends its application range of aerospace companies, medical device makers, and limited-production automakers. It has been reported that carbon fiber reinforced thermoplastic composites were possessing improved mechanical properties including: tensile strength, Young's modulus, toughness, yield strength, and ductility and flexural, Ning et al. [73].

Masood and Song [51] detailed the development of the feedstock filament from the composite material using a single screw extruder (schematic given in Fig. 7(a)). Loading of abrasive/filler particles in parent plastic (nylon/ABS) can be decided based on the requirements and technical specifications of the FDM setup. The selected composite mixture powder is first mixed in appropriate proportions of plastic, abrasive/filler and surfactant/plasticizer and homogeneous mixture is prepared by compounding procedure and is dried under vacuum in an oven (see Fig. 7(b)). The maximum volume of the mixer is 55 cm^3 per mix approximately and one to three hours mixing time, Sa'ude et al. [74]. The mixture is then fed into the hopper (shown in Fig. 7(c)) which flows by gravity from the feed hopper down into the extruder barrel to fill the annular space between the extruder screw and barrel (refer Fig. 7(d)). Barrel is stationary and screw is rotating so frictional forces will act on the material, barrel and screw surface. Die and barrel temperature are adjusted from the panel and material melts as it flows forward. As the melting point of plastic exceeded, a thin film of composite material as compounded will form on the barrel surface. In the melt-conveying zone, the material is simply forced towards die head (Fig. 7(e)). Since the die exerts a resistance to flow, a pressure is required to force the material through the die and is determined by the shape of the die. The extruded filament exiting the die is then carried away, through water tank by a take up roller (Fig. 7(f)) and wounded on the spool.

3. AM techniques

Following is the brief introduction of some of the AM techniques which are frequently used for biomedical applications:

3.1. Selective laser sintering (SLS)

In early 2000, researches have been carried out for fabrication of porous biomedical structures using a biological complex of sufficient mechanical strength.

In these types of foot-stepping researches, the basic criteria for building a biologically compatible matrix for tissue engineering constructions has been established on the basis of: prevention of cytotoxicity, maintenance of adhesion, fixation, proliferation, prevention of inflammatory reaction, immune response, sufficient mechanical strength, bio-resorption through metabolic routes, etc. [75,76]. Xie et al. [77] developed 316L parts through SLS performing of EVA-coated metal powders, debinding and sintering in hydrogen atmosphere (refer Fig. 8). The effects of processing parameters on pore characteristics and mechanical properties were analyzed. The results indicated that the porosity of green body, mainly depends on the laser energy density, while the pore features and mechanical properties of sintered specimens are largely dominated by sintering temperature. Cheng et al. [78], produced Ti–6Al–4V materials through SLS with variable porosity that structurally mimicked human trabecular bone. Their results indicated that a higher porosity constructed mimicking trabecular bone structure was capable of stimulating osteoblast differentiation when compared to 2D and low porosity constructs.

Ghita et al. investigated laser sintering of virgin and used polyether ketone (PEK) powder, performed with a high temperature polymer laser sintering machine. Physico-chemical results of their study revealed that, used PEK has a viable processing window for laser sintering in combination of optimized specific parameters. It has been outlined that incorporation of 30% used PEK powder led to 17% reduction in tensile strength [79]. Wang et al. performed an experimental study and simulation of laser sintered WC-Co hard metal powders. The influence of various process parameters (such as: laser power, scans spacing and speed, powder mixture ratio, grain sizes and shapes) was inspected for their effect on mechanical quality of fabricated parts [80]. Shishkovsky et al. investigated the technical aspects of producing porous biocompatible medical implants of NiTi and Ti alloy through SLS. The finally fabricated parts were subjected to mechanical properties, microstructure, corrosion behavior and comparative results of NiTi and Ti alloy were presented. The extensive experimentation carried out in their research work helped in determining their suitability for use as functional implants [81]. Eosoly et al. manufactured HAp/poly-ϵ-caprolactone tissue engineered scaffolds and highlighted the influence of SLS processing parameters on the qual-

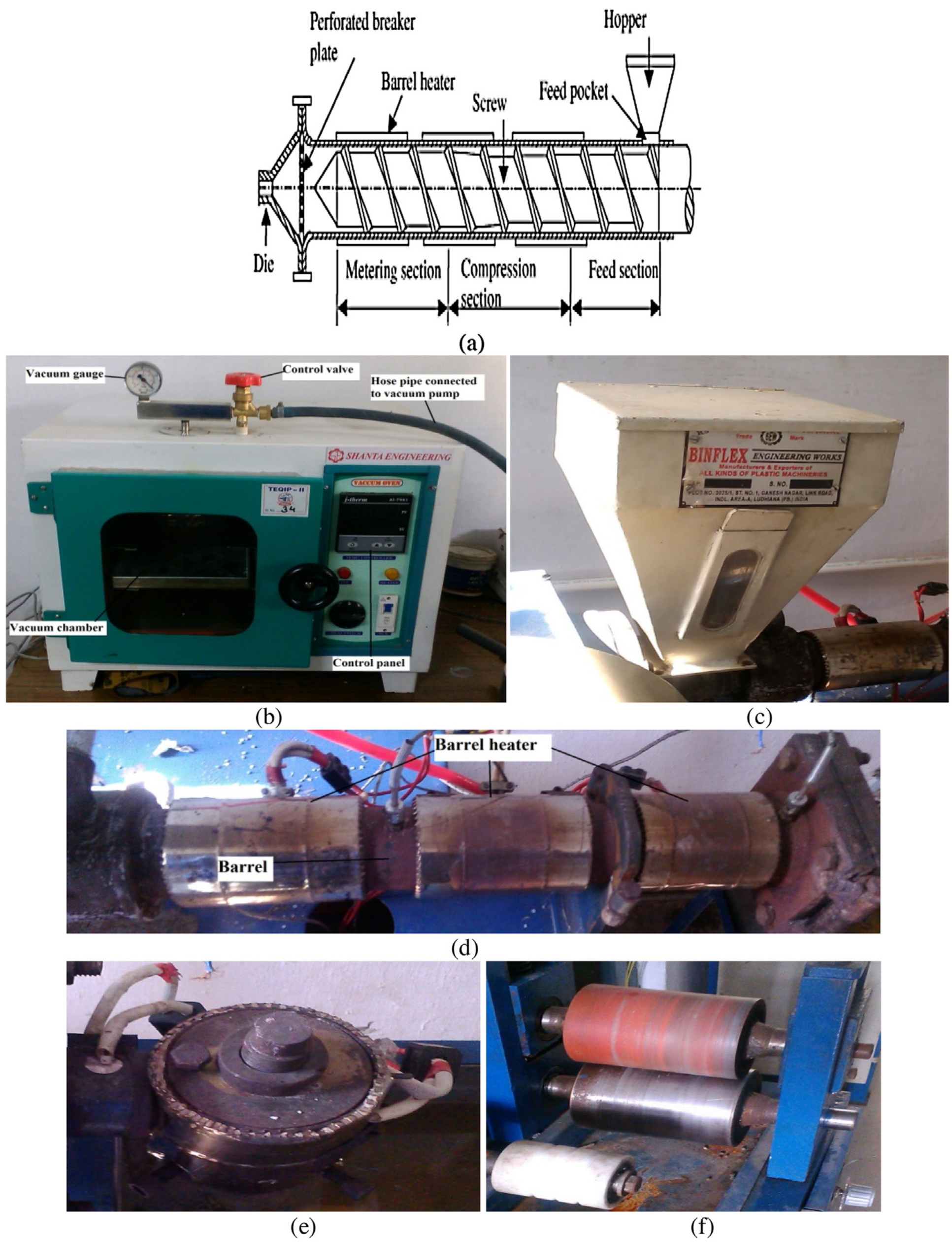

Fig. 7. Equipments/tools required for development of FDM filament.

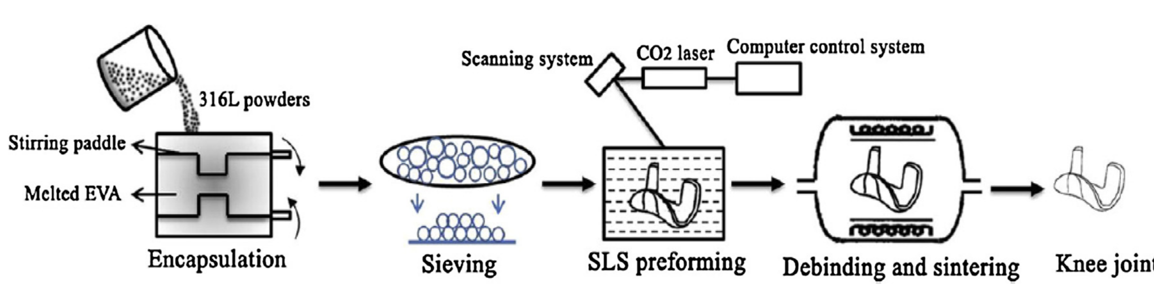

Fig. 8. Fabrication of SS-316L through SLS.

ity of fabricated parts. The analysis showed that the dimensional accuracy and mechanical behavior of scaffolds with a designed relative density of 33% are strongly dependent on the manufacturing direction and scan spacing [82]. Similarly, Salmoria et al. prepared functional graded scaffold with HAp reinforced HDPE having interconnected pores diameters of 30–180 μm and porosity of 45–48%. The storage modulus of the composite scaffolds was found to be decreased with an increase in HAp content [83]. Shuai et al. fabricated PLGA/*n*-HAp composite porous scaffolds with controlled pore architectures and by exposing bioactive ceramics to scaffold

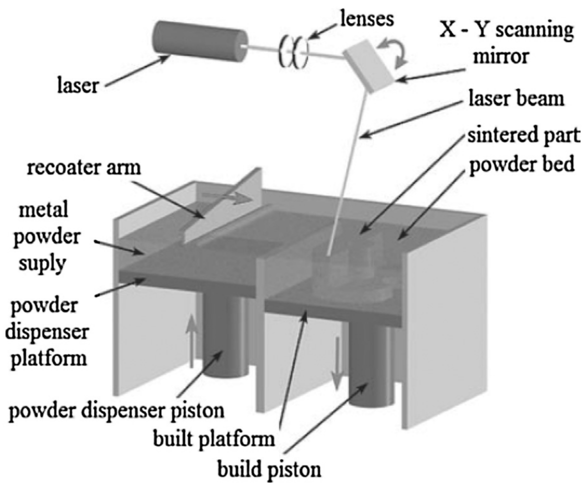

Fig. 9. Schematic of DMLS.

surface via SLS. In their work, they have studied the effect of *n*-HAp content on the microstructure and mechanical properties of resulting scaffold through SEM analysis and tensile testing, respectively. It has been found that the introduction of *n*-HAp particles in PLGA has improved the mechanical properties of the polymer porous scaffolds [84].

Xie et al. prepared porous SS-316L by SLS pre-forming of ethylene-vinyl acetate copolymer coated metal SS-316L powders. The results indicated that the porosity of green part was dependent on the laser energy density and after sintering, at 1100–1300 °C, mechanical properties of the parts was significantly improved. It was highlighted that the pore structural parameters and mechanical properties can be matched with those of trabecular bone at optimized SLS processing parameters and sintering temperature [77]. Recently, it has been found that *n*-HAp particles reinforced composite bio-devices made with SLS are crystalline, bioactive activity and osteoconduction, which are very beneficial for bone in-growth [85]. Further, SLS is more common for making polymeric based bio-devices as very little research has been carried out on the use of SLS for metallic implants and equipments.

3.2. Direct laser metal forming/sintering (DLMF/DLMS)

Shibli et al. performed a histological study in order to evaluate bone to implant contact around immediately loaded DLMF transitional implants retrieved from human posterior maxilla. For their study, twelve totally edentulous patients were considered for comparing immediately loaded and unloaded implants (manufactured with DMLS as shown in Fig. 9), placed between conventional implants. After a period of 8 weeks, the conventional implants and the surrounding tissue were removed and prepared for histomorphometric analysis and it was found that immediately loaded implants were having a higher bone to implant contact [86].

A custom Condylar plate of Ti–6Al–4V alloy obtained by the DMLS process was tested for its mechanical strength and accuracy of geometry through tensile strength & micro hardness test and ANSYS® software respectively. It has been found that DMLS technology has a wide scope for fabricating craniofacial and maxillofacial implants due to their high strength and hardness. Further image processing software attested the accuracy of fit of the prosthesis to use in human mandibles [87]. Pattanayak et al. [88] studied SLM processing conditions (such as: laser power, scanning speed and hatching pattern) to obtain a dense product of Ti powder (particle size less than 45 lm). The results of the showed that a fully dense plate thinner than 1.8 mm was obtained when the laser power to

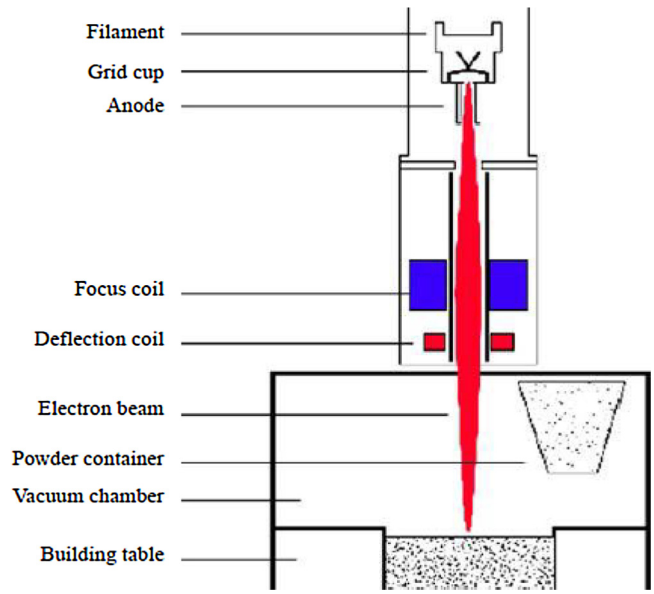

Fig. 10. Schematic diagram of electron beam melting process, [144].

scanning speed ratio was greater than 0.5 and the hatch spacing was less than the laser diameter, with a 30 lm thick powder layer. The compressive strength was in the range 35–120 MPa at 75–55% porosity. Field emission scanning electron micrographs showed that finer networks of titanium oxide were formed over the whole surface of the porous body. Further, in-vivo study showed that new bone penetrated into the pores and directly bonded to the walls within 12 weeks after implantation into the femur of Japanese white rabbits. Majumdar et al. deposited Co layers on Ti–6Al–4V substrate surface through a modified DMLS process called direct laser cladding. The modified DMLS process led to formation of defect free microstructure with the presence of Ti_2–Co and Ti–Co and Co_2–Ti at the interface which improved the bio-compatibility of the fabricated parts, Majumdara et al. [89]. Traini et al. [90] prepared functionally graded titanium parts by DMLS procedure using a Ti–6Al–4V alloy powder. The morphological and chemical analyses were performed by SEM and energy dispersive X-ray spectroscopy. It was found that The Young's modulus of the inner core material was 104 ± 7.7 GPa, while that of the outer porous material was 77 ± 3.5 GPa. The fracture face showed a dimpled appearance typical of ductile fracture.

3.3. Electron beam melting (EBM)

EBM (refer Fig. 10) found numerous applications in aerospace, automotive and medical/orthopaedic implant industries.

During the EBM processing, each slice is divided into two regions, i.e. contours and squares. Initially the boundaries of the parts (act as counters) are fabricated which acts as an interface between the part and the surrounding metallic powder. After this the required part was built within these contours, normally referred as squares. The process is performed under vacuum condition to eliminate impurities and yields high strength properties of the finished part. The final built incorporates porosity lattice structure and scaffold to help in bone growth. Once the build is finished, the parts remain inside the built chamber for cooling. The part after its fabrication is transferred to a special blast chamber with a powder recovery system (PRS) where all the excess powder is removed. Further, processes such as milling, turning, polishing and grinding can be used for surface treatment of EBM parts [91].

Heinl et al. fabricated novel cellular Ti–6Al–4V structures for orthopaedic applications with EBM. Microcomputer tomography

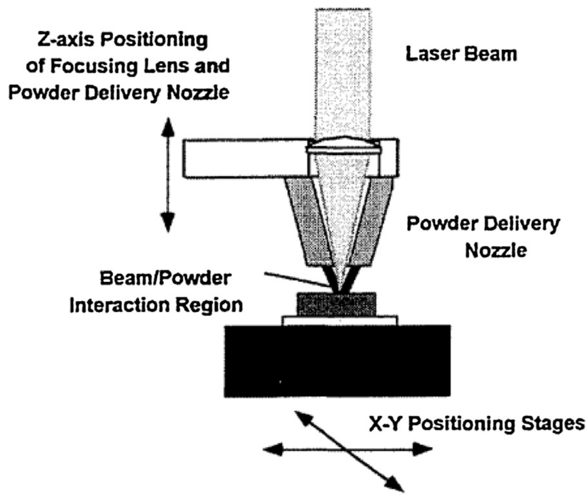

Fig. 11. Schematic of LENS, [145].

analysis carried out in their research work has demonstrated the capability of EBM to fabricate 3D structures with an interconnected porosity, suitable for tissue in-growth and vascularization. Surface of the resulting implants has been modified with HCl and NaOH solutions which induced apatite formation during in-vitro bioactivity tests in simulated body fluid [92]. Liu et al. in 2016 [93] manufactured β-type Ti–24Nb–4Zr–8Sn porous components with maximum 70% porosity and subjected these specimens to aging treatment. EBM made components exhibited about two times strength-to-modulus ratio as compared with porous Ti–6Al–4V components having the same level of porosity.

3.4. Stereolithography (SLA)

The model is initially designed through CAD (in case of ordinary model) software and CT/MRI scan data (in case of bio-manufacturing) is converted into slices of known dimensions i.e. .STL format and finally transferred to SLA apparatus for building. The laser beam moves in sequential cross-sectional increments of 1 mm (max.), corresponding to slice intervals [94].

The laser beam is computer controlled and directed to trace the layer, the polymer solidifies and the excess areas are left as a liquid. After completion of the one layer, the build platform is lowered by a distance equal to the layer thickness (normally ranges between 0.003–0.002 in.), and a subsequent layer is formed on top of the previously completed layers. This process goes on repeating the above said procedure until the last layer of the model/prototypes is traced by the laser. Most of SLA parts need to be cured in a UV oven for improving mechanical properties of the prototypes. The 80% of polymerization takes place inside SLA while remaining 20% completes in UV oven. Depending upon the requirements, one may also go for post treatments such as: polishing, sanding, painting and finishing [95]. Earlier, it was used in maxillofacial and oral surgery by Brix and Lambrecht in 1985 and 1987 [96]. In 1991, human anatomy models produced with SLA was first used in a maxillofacial surgery clinic in Viena [97]. In 2000, biodegradable structures were produced by SLA technique [98]. Maji et al. in 2008 [99] at CMERI used SLA process for the development of master pattern for IC process.

3.5. Laser engineered net shaping (LENS)

Balla et al. in 2007 [100] carried out extensive research work for coating Yttria-stabilized Zirconia coatings on SS alloy by using LENS technique (as shown in Fig. 11).

Due to high thermal gradients and cooling rates in LENS, a very fine coating microstructure with 1700–2000 HV was produced. This technology allowed having simultaneous control over the composition and micron level features of coatings. Krishna et al. in 2009 [101] fabricated porous NiTi alloy with 12–36% porosity using LENS technology and studied the effects of processing parameters of LENS on density and other properties of NiTi samples. The density of the samples was found to increase drastically by increasing the specific energy input to 50 J/mm^3 and further increase in specific energy input had negligible effect on density. With 12–36% porosity, NiTi sample exhibited low elastic modulus (between 2 and 18 GPa) as well as high compressive strength and recoverable strain. It was highlighted that porous NiTi alloy samples have the potential to accelerate the healing process and improve biological fixation when implanted in-vivo.

Balla et al. in 2009 [102] made Ti–TiO_2 based novel structures with functional gradation using LENS technology. The functionally graded structures having variable concentrations of TiO_2 ceramic were found to be non-toxic and biocompatible and improved the hardness, surface wet-ability and formation of chemisorbed lubricating films. These unitized structures with open porosity at one face, low friction surface on other face can eliminate the need for multiple parts with different compositions for load-bearing implants such as total hip prostheses.

3.6. Fused deposition modelling (FDM)

FDM technology is one of the most widely used AM technique which was established in the late 1980's and several series of machines such as FDM Titan, FDM Dimension, FDM Vantage, FDM Maxum, FDM 3000 and FDM Prodigy Plus have been developed, Bakar et al. [103]. Kumar et al. [104] illustrated the working of FDM process, dispenses two materials-one material to build the part and the other material for a disposable support structure. The material is supplied from a roll of plastic filament on a spool. To produce a part the filament is fed into a temperature-controlled extrusion head and heated to a semi-liquid state. The head extrudes and directs the material with precision in ultra thin layers onto a fixtureless base. The nozzle has a programmed mechanism which allows the flow of the melted material to be turned on and off. The result of the solidified material laminating to the preceding layer is a plastic 3D model built up one strand at a time. The system operates in X, Y and Z axes, drawing the model one layer at a time. The filament is extruded in a thin ribbon form confirms the bond of filaments at each layer, Liou [105]. The extruded filament which is deposited onto the platform is recognized as a 'road', Grimm [106], Bellini et al. [107]. A road will be quickly solidified after being stacked by another layer of road on the platform. The road that deposited earlier, which will be stacked by the latter road, is called a substrate. Support structures are automatically generated for overhanging geometries and are later removed by breaking them away from the object, Upcraft and Fletcher [108]. The FDM process starts with importing a .STL file of a model into the pre-processing software. This computer software slices the 3D model into thin layers. Process parameters like; tip size, material type and machining speed are automatically added and the control file for the machine is generated, Greul et al. [109]. This model is oriented and mathematically sliced into horizontal layers varying from 0.127 to 0.331 mm thickness. Fig. 12 represents the schematic of FDM.

Two separate nozzles are used for model material and support material. For example in Stratasys uPrint-SE system, support material (SR30-XL) is water soluble while model material (P430-XL) for the same system is insoluble. The finished part can easily separate out by exposing the part prototyped by FDM (containing the model and support material) to water.

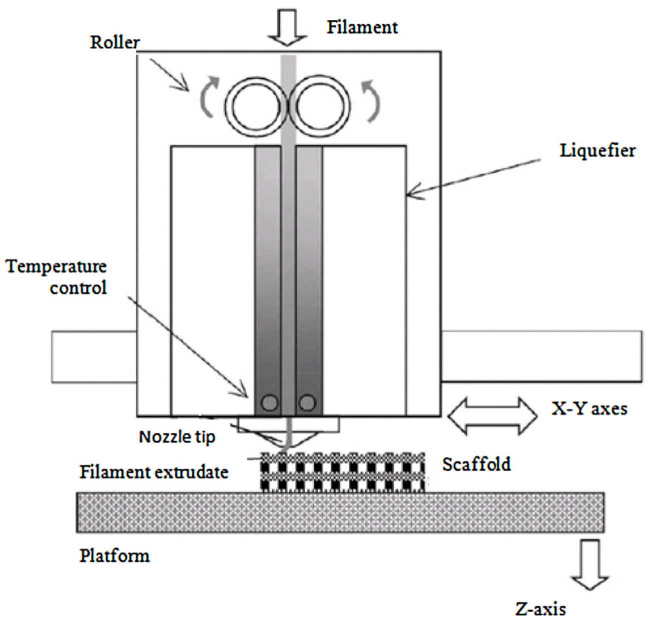

Fig. 12. Schematic of FDM.

Table 4
Standard FDM materials [60].

S. no.	Description	Grade
1	Acrylonitrile butadiene styrene	ABS plus
2	Acrylonitrile butadiene styrene	ABS-M30
3	Acrylonitrile butadiene styrene	ABS-M30i
4	Acrylonitrile butadiene styrene	ABSi
5	Polycarbonate acrylonitrile butadiene styrene	PC-ABS
6	Polycarbonate	PC
7	Polycarbonate	PC-ISO
8	Polyphenylsulfone	PPSF/PPSU
9	FDM thermoplastic material	ULTEM 9085

Though, fabrication of biomedical implant is a tailor-made process which means size, geometry and attributes of joints or implant varies with person to person. Medical implant fabrication starts with MRI or CT scan of the patient and then scanned data is converted into 3D geometry using MIMICS or 3D-doctor software package, and finally fired into the FDM machine. Table 4 shows standard materials for FDM applications.

The main limitation of FDM is its inferiority in-terms of the mechanical properties of the resulting prototypes. This led to the development of various types of alternative materials in order to improve the application domain of this technology. However, this task is not so easy and demands lots of time and efforts.

3.7. Fabrication of medical implant/scaffold with FDM

Woodfield et al. [110] used a FDM technique for producing Poly (Ethylene Glycol)-Terephthalate-Poly (Butylene Terephthalate) (PEGT/PBT) block co-polymer scaffolds with a 100% interconnecting pore network for engineering of articular cartilage. It was found that through variation in co-polymer composition, porosity and pore geometry, the scaffolds developed were produced with a range of mechanical properties close to articular cartilage. The scaffolds seeded with bovine chondrocytes supported a homogeneous cell distribution and subsequent cartilage-like tissue formation. Drexel University developed a variation of FDM called Precision Extruding Deposition (PED) for fabrication of bone tissue scaffolds. In this process, material in pellet or granule form was fed into a chamber where it was liquefied. Pressure from a rotating screw forces the material down a chamber and out through a nozzle tip. This process was used by Wang et al. [111] to directly fabricate PCL scaffolds with controlled pore size of 250 μm. Ang et al. [112] developed a Rapid Prototyping by using the same principle as the 3D bioplotting system to produce chitosan-hydroxyapatite scaffolds. The literature review reveals that no work has been carried out for the development of feather/wool reinforced PMC filament for the fabrication of customized scaffold/articular cartilage through FDM process. Zeng et al. [113] designed a methodology to develop ear scaffold (refer Fig. 13) of polyurethane with good dimensional accuracy and shape, good flexibility, bio-compatibility and elastic modulus. This method can provide an efficient way for macrotia reconstruction and avoids the difficulties of carving cartilage and alleviate chest pain in traditional operation.

Gronet et al. [114] used anatomic models as templates to simplify the formation of custom implants. In their research work, two patients (first suffered from the posterior fossa defect and second from large cranial defect) were considered for restoration with FDM technology. Anatomic models of these patients revealing the margins (refer Fig. 14), were fabricated using FDM. Zeltinger et al. [115] investigated the influence of pore size and porosity on cell adhesion and proliferation by Disc shaped Poly(L-lactic acid) (L-PLA) scaffolds measuring 10 mm (diameter) by 2 mm (height) were produced through both 3DP and salt & leaching methods. Lam et al. [116] developed a blend of starch-based powder containing corn starch (50%), dextran (30%) and gelatine (20%), bounded by printing distilled water.

Cylindrical scaffolds were produced measuring 12.5 mm (diameter) by 12.5 mm (height) and infiltrated with different amounts of a copolymer solution consisting of 75% L-PLA and 25% polycaprolactone in dichloromethane to improve their mechanical properties. Drescher et al. [117] used a low cost 3D printer and generated porous biopolymer scaffolds with interconnected pores to analyze the feasibility, geometrical accuracy and quality.

The results have shown that highly porous scaffolds with different pore geometries and sizes can be achieved with a low-cost printer. Although the focus of this article is on the fabrication techniques and biomaterials used in FDM, the degradation kinetics and byproducts of the materials are in fact a very significant problem in 3D scaffolds due to mass transport limitations within thick scaffolds. This is a moving boundary diffusion-reaction problem that even without bio-degradable biomaterials can result in hypoxia and acidosis within the scaffolds. So there is a possibility that the use of organic fibers such as feather and wool results in more stability of the scaffold in the human body. The upcoming section highlights some of the applications of organic fiber reinforced natural polymers.

3.8. FDM based natural composites for biomedical applications

In last one decade, researchers have realized that unless natural resources are protected and his life has a threat. Further, conservation of forests and optimal utilization of agricultural and poultry waste has become important topics worldwide. Research on biodegradable polymeric composites, can contribute for green and safe environment to some extent. In the biomedical and bioengineered field, the use of natural fiber, mixed with biodegradable and bioresorbable polymers can produce joints and bone fixtures to alleviate pain for patients. According to [150], biomaterial can be defined as a material used in implants or medical devices, intended to interact with biological systems. Use of natural fibers (such as; leaves from flax, jute, hemp, pineapple and sisal) may help in improvement of biological characteristics for developing natural composites. An animal fiber generally is comprised of proteins such as collagen and keratin. It can be divided into animal hair and silk. Animal hair fiber is defined as the fiber, which is taken from

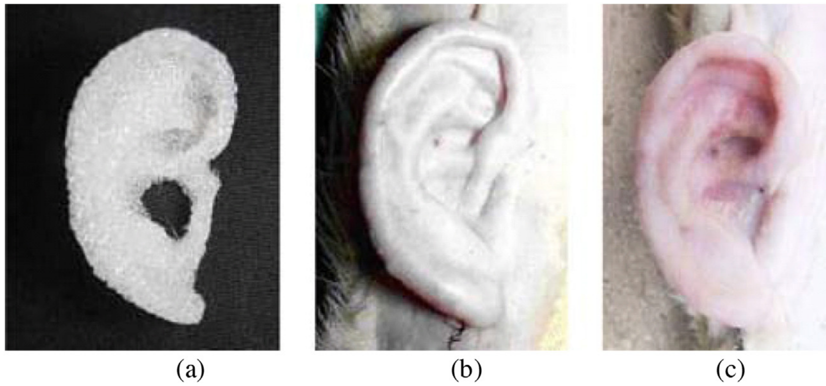

Fig. 13. Ear framework (a), reconstructed ear after operation (b) and reconstructed ear after 12 months, [113].

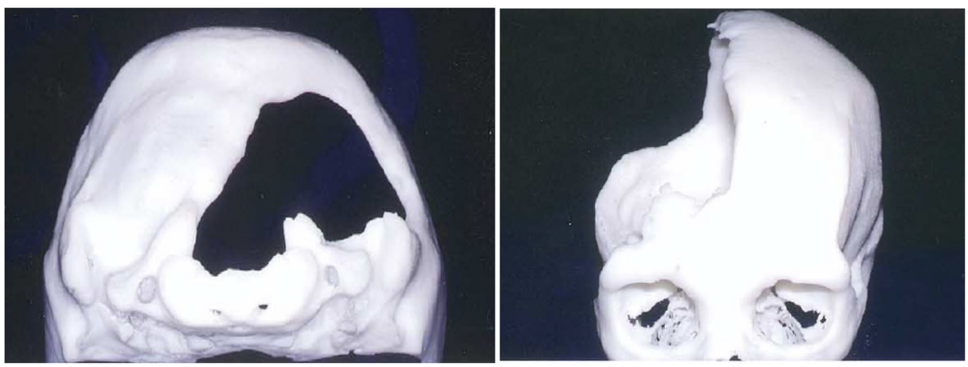

Fig. 14. Posterior fossa defect (a) and large cranial defect (b), [114].

animals and hairy mammals. Examples of animal hair are sheep's wool, cashmere, alpaca hair, horse hair. Sheep's Wool is mainly composed of a-keratins, a protein which mainly forms the horny layer of the epidermis and of epidermal appendages such as hair. Wool is a multi-component fiber, which consists of about 170 different protein molecules and these protein molecules constitute the morphological components of wool, Zahn et al. [118]. The diameter of wool fiber is in the range of 20–40 lm and the cross-section is elliptical, Simpson and Crawshaw [119].

The wool fiber is typically divided into three morphological components, including cuticle, cortex and cell membrane. The microfibrils in the cortex represent approximately 50–60% by mass of the cortex material, the bonding between the microfibrils and their embedding matrix within the cortex and the presence of the organized helices within the microfibrils dominate the mechanical and water absorption properties of wool fibers, Feughelman [120]. Chicken feathers (schematic shown in Fig. 15) are approximately 91% protein (keratin), 1% lipids, and 8% water. Their fiber diameters were found to be in the range of 5–50 lm, Kock [121].

The keratin particles had a heterogeneous nucleating action on polypropylene crystallization that increased the overall crystallization rate. The nucleation density increased as a function of the keratin amount in the composites. The crystallinity, the crystal dimension and the long period of the polypropylene were found to be dependent on the crystallization condition and the composite composition, Canetti et al. [122].

Materials derived from poultry feathers can also be used advantageously as the reinforcing materials in polymer matrix composites. Such applications can potentially consume the huge quantity of feathers produced annually as a by-product of various poultry units worldwide. Chicken feathers are approximately 91% protein (keratin), 1% lipids, and 8% water, Schmidt [123]. The amino acid sequence of a chicken feather is very similar to that of other feathers and also has a great deal in common with reptilian keratins from claws, Bitter [124]. A recent study showed that the PLA, Chitosan and keratin composites, support osteoblast attachment and proliferation during short-term culture indicating that these composites might be promising materials for medical application, Tanase and Spiridon [125]. The use of such reinforcement materials for development of filament material that could be used to fabricate scaffolds or articular cartilage seems to be very promising.

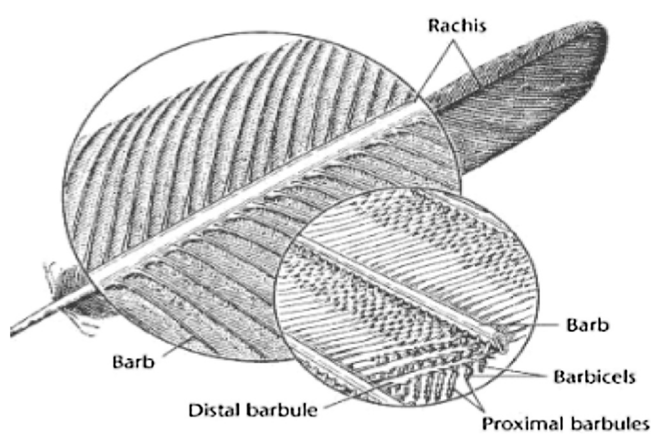

Fig. 15. Different parts of chicken feather.

3.9. Hybrid digital AM

The term digital manufacturing is known for a manufacturing system wherein the system controls are fully or semi controlled with the help of sensors, actuators, internet, high performance computers and also simulation softwares. Such manufacturing systems are having interoperability, enriched modelling, system automy, real-time insights, modularity, etc. Through the platform of hybrid digital AM, one can club additive and subtractive manufacturing processes into one single unit and this unit can be controlled through computer insights (such as CNC programs). Moreover one may also think of clubbing two or more types of AM systems in order to produce multimaterials systems for high performance applications. Last but not least, part fabrication (with AM) and its post treatment can be carried out under one head. The hybrid AM merges the boundary line between component development and system integration. The co-integration of roll-to-roll manufacturing technology with AM techniques will lead to entirely new products and markets, Joshi et al. [126].

Joshi et al. [127] highlighted the sope of hybrid AM technologies for printed electronic sector as an advanced device integration platforms and new markets. Design-driven manufacturing and capabilities of AM systems are being exploited for a variety of innovative applications ranging from unique or specialized functional components to more advanced large-scale applications such as medical and dental, building construction, aerospace and automotive manufacturing, 3D electronic devices, consumer products and Microsystems, added by Joshi et al. [127]. Kerbrat et al. [128] highlighted a new hybrid modular design methodology for collaborating additive and subtractive technologies in order to meet the design for manufacturing agenda of globe. This method has been developed as a new DFM system in CAD software. It is one of the first attempts to expand the DFM concept to a multi-process situation, combining additive processes (such as SLS or powder projection) to more traditional subtractive ones in a hybrid modular vision. Two industrial examples taken from the field of tooling have been treated to illustrate the possibilities of this new methodology, and the way it can be used in an industrial manner.

Liou et al. [129] outlined a digital hybrid AM system which uses a laser deposition system (Rofin-Sinar 025-for material deposition) and a CNC milling (Fadal VMC-3016L-for material removal). The laser deposition system and CNC milling machine worked inshifts in a five-axis motion mode, which reducted the build time of the part and necessitates a time-consuming post processing. Bonnard et al. [130] proposed to use STEP-NC concept, containing high-level information, in order to integrate the AM with multiple machining processes such as milling, turning, etc., through a single interface. Such STEP-NC digital chain will work in accordance with the norm work group committee ISO TC 184/SC 1. Kostakis and Papachristou [131] have examined the feasibility of a RepRap based Lego-built three-dimensional (3D) printing-milling machine (framework model is given in Fig. 16). In their work they have fisrt examined the modularity of the process development and hardware components for tangible products and then demonstrated the hybrid 3D printingmilling machine for its potential of digital fabrication.

Li et al. [132] presented a novel hybrid AM technology combining digital light projection SLA with 3D micro-dispensing alongside conventional surface mount packaging. It has been believed by the inventors that this technology will overcome the inherent limitations of individual AM processes and integrates seamlessly with conventional packaging processes to enable the deposition of multiple materials. This will facilitate the creation of bespoke endues products with complex 3D geometry and multi-layer embedded electronic systems. In their work, a demonstration of a polymer pyramid with embedded triple-layer 555 LED blinking circuitry (refer Fig. 17) was successfully fabricated to prove the technical viability.

Friel and Harrisa [133] manufactured componenets with ultrasonic-AM, a hybrid form of manufacture. The unique nature of the process permits extremely novel functionality to be realised such as multi-material structures with embedded componentry.

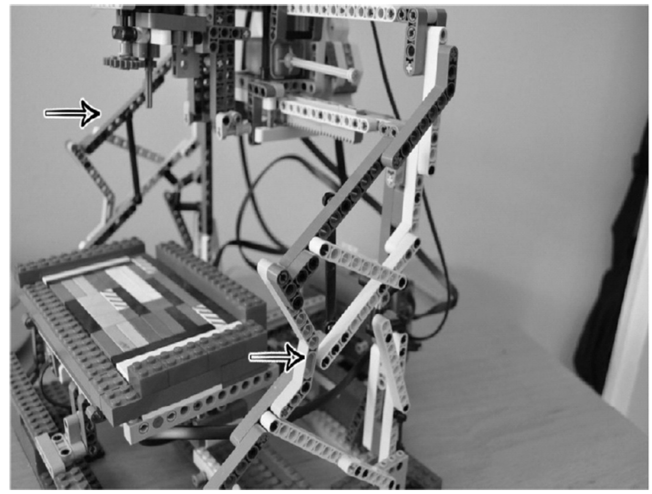

Fig. 16. Framework of a RepRap based Lego-built three-dimensional (3D) printing-milling machine, [131].

Process fundamentals for ensuring quality of bonding is maximised and that this is monitored through suitable techniques such as peel testing. Similarly, Karunakaran et al. [134] presented a hybrid layered manufacturing process which combined the best features of additive and substractive manufacturing approaches. In this process the near-net shape of the object is first built using weld-deposition; the near-net shape is then finish machined subsequently. Time and cost saving of this process can be attributed to reduction in CNC programming effort and elimination of rough machining.

Although various researchers have invented different types of hybrid AM system yet there is still a way long distance to travel from laboratory experimentations to production lines. For this, joint venture of academicians and industries is required for commercialization of such hybrid technologies in order to meet with industrial requirements. However, some of the top industries such as: SIEMENS™ and OPTOMEC® already in hybrid AM market but the capabilities of their products in-terms of quality characteristics are yet to document.

4. Technology road map from the materials perspective

Materials issue of available AM technologies is one of main limitations which restrict on-going researches to explore different areas of applications. Generally, AM techniques are designed and developed to process particular category of materials and beyond which one need to either modify the hardware of the system or to develop a compatible workhorse material. The development of new materials will represent next great innovations in this field and is believed to provide researchers a pathway to tackle radically different processing conditions. For example, FDM is a plastic based technology, which usually unfits for those products which are required to possess high strength, electrical conductivity, magnetic conductivity, constructional components, fire hazardous systems, human implants and many more. However, various research activities, till date, were focused for the enhancement of workhorse materials through the collaboration of plastics, metals and ceramics. But very less has focused to develop commercial standards for testing of such materials and their resulting parts. Moreover, consistencies in-terms of mechanical, physical and metallurgical properties are yet to establish for these alternative materials based components. In order to tackle such critical issues, followings roadmaps should be taken care of:

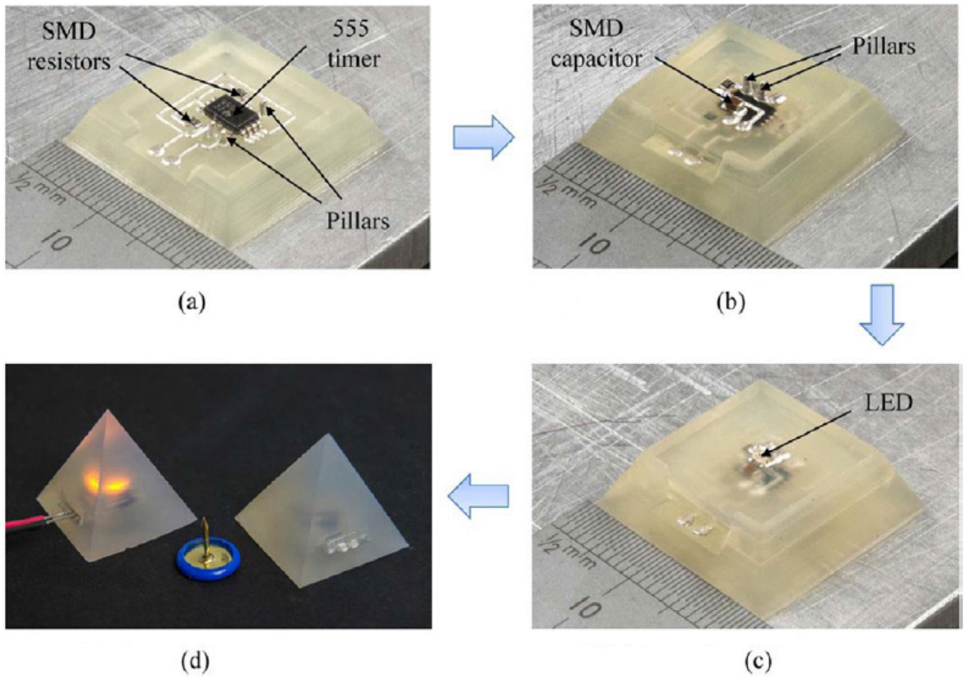

Fig. 17. First layer circuitry (a), second layer circuitry (b), third layer circuitry (c) and finished samples (d), [151].

- ◯ Explore the actual field of problem.
- ◯ Build problem relevant knowledge.
- ◯ By establishing research facilities.
- ◯ Training of personnel.
- ◯ Involvement of individuals from industries.
- ◯ Adoption of industrial standards.
- ◯ Material research and development.
- ◯ Establishment of materials and products.
- ◯ Sharing project outcomes.

This roadmap will enable integrated design methodologies for materials, processes, development of relation among process-structure-property, establish feedstock testing protocols and explore next-generation AM materials.

5. Conclusions

AM techniques have occupied a key position in the modern manufacturing sector. Especially in biomedicine, AM has shown its capabilities of producing customized implants successfully overtaken most of traditional manufacturing process, and occupied a key position in most of From the present review, it has to conclude that with the emergence of AM technologies, medical services have matured enough to tackle critical health issues rapidly and precisely. However, limitation of almost every commercial AM techniques is their rigid choice of processing material, is still unresolved. Due to this, the part fabricated with AM requires post treatments for improving their surface characteristics, especially in the case of biomedical applications. Further through the production of in-house workhouse materials for various AM techniques, problems like: cost of materials, limitation among the selection of workhorse material and limited physical, mechanical and metallurgical properties of prototypes can be resolved. The future studies may also focus on the development of parts with integrated magnetic and non-magnetic properties for electronics and electrical applications.

Particularly for FDM, lots of developments have been taking place for the development of applications based filament materials. However, very less has highlighted the use of chicken feather based organic fibers. In literature, these feathers are established as protein enriched sources and their use for the fabrication of FDM based customized scaffolds may result in better in-vivo/in-vitro properties.

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