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CURRENT STATE, CHALLENGES AND FUTURE NEEDS OF ADDITIVE MANUFACTURING

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ABSTRACT

Additive Manufacturing (AM), the process of joining materials to make real 3D object direct from 3D CAD data, usually adding layer upon layer, this (material joining) technique is also knowing as rapid prototyping or 3D printing. It has many advantages over traditional manufacturing process. It provides a way to produce cost effective, complicated geometries, customized products and advanced material properties. This paper focus on current state and challenges in the technology and future needs for rapidly emerging technology. Also gives an overview of 3D printing, benefits, drawbacks and future research and development.

Keywords: *Additive Manufacturing, Computer aided design, current state, applications, challenges, future needs.*

Introduction

In the early stage, this material addition technology was known as rapid prototyping. Firstly, this technique was developed in the mid-1980s by the 3D Systems Inc.'s (Valencia, CA) SLA-1, with the idea of making the prototypes or model from the direct 3D data which is created using AutoCAD or Pro-E [1-2]. From the beginning to now this technology has achieved significant growths in part accuracy, speed and material properties. This emerging technology is now known as additive manufacturing (AM) by the manufacturer and 3D printing by the common people [3]. Recently ASTM (American Society for Testing and Materials) standard F-2792 defines it as: "Additive manufacturing (AM) is a process of joining materials to make objects from 3D model data, usually layer upon layer deposition, as opposed to subtractive manufacturing technologies" [4]. Applications of this technology include the fabrication of different types of prototypes and models, further these prototypes are used for visual inspection and functional testing in various stages of the product development process [5], (Figure 1) and it is also helpful in complicated product design and development time cycles [1]. It is reported that using AM can reduce production cost up to 70% by saving raw materials input and to introduction time in the market by 90% [6].

Technology overview

Common AM processes which is used worldwide for fabrication process are stereolithography (SL), fused deposition modeling (FDM), selective laser sintering (SLS), laminated object manufacturing (LOM), 3D printing (3DP), electron beam melting (EBM), polyjet printing (PP), and laser engineered net shaping (LENS). See figure 2, All these processes include common features input of raw material and supply of heat energy (either in the form of laser beam or electron beam), but all the fabrication process have some differences in their printing processes, but all the processes uses same manufacturing philosophy, as the model is built by layer by layer deposition of raw materials, rather than removing materials as in conventional manufacturing processes [7]. The main advantages of this technology are that it does not require any changes in tool, and fixture as compared to subtractive manufacturing [8].

Fused deposition modeling

Stratasys introduced Fused deposition modeling in 1991 [5]. This technique uses a nozzle to force out a thermoplastic material in a semi molten form to make the physical object from layer by layer deposition of the material. In layer by layer deposition process each new layer bonds with the previously build layer and solidify. Now a days FDM system uses two nozzles; one for the support material and other for the part material as shown in Figure 3 (a). Once the final part is fabricated it removed from the platform for final processing (support material removal and surface finish improvement). Initially FDM was used for creating the prototypes and toys but now it is also used for creating functional parts with a good geometrical accuracy. But it has been observed some drawbacks such as lower building speed and lower surface quality [10-12].

Inkjet Printing

Inkjet printing techniques are two types

Binder jetting

In this technique a binding material is jetted trough the nozzle and sprayed into a power bed of material to fuse it a layer at a time to create the required part. After completing one-layer next layer of powder is sprayed and smoothen by roller on the table and a binding material is jetted through the nozzle to bind them into a layer, same process is repeated until the final object is created. A range of different materials such as ceramics and food may be used in this process. A full color can be easily added to the binder, this is the main advantages of this process. The only drawback of this technology is the part created from it are not as strong as like sintering process.

Material Jetting

In material jetting process, the actual build material and the binder mix-up (in liquid or molten state) are selectively jetted through multiple jet heads to create a layer. A separate nozzle is also provided for support materials. Each deposited layer is cured by UV light. This process is repeated until final product is created. This technique is a very precise 3D printing method, producing accurate parts with a very smooth surface finish.

Stereolithography (SL)

SL was introduced by 3D Systems in 1987 [14], it is first and most widely used rapid prototyping process. This process consists of a build platform, which is mounted in a vat filled with liquid monomer resin (acrylic or epoxy resin), recoating blade and an ultraviolet helium-cadmium laser or argon ion laser.

The surface layer of monomer resin is cured selectively by the laser beam, which follows the same path as generated in sliced model. As soon as one layer is created, the movable platform is lowered (equal to the thickness of one layer) into the vat and a fresh liquid resin is spread over the last solidified layer and then it again cured by UV. The whole process is repeated until the final object created. After completing the part, it is removed from the platform. Post-curing is required to completely solidify the prototype. A high accuracy and smooth surface finished parts was created in this technique, the drawbacks of this process are costly, time-consuming, and toxic material used, post-processing required and need support structures which may affect the surface finish when it removed [14-16].

Power bed Fusion

In powder bed fusion process, a very thin layer of powder is sprayed into the platform and rolled by a roller to maintain the uniform thickness over the bed. A laser beam is used to fused the powders particles to form a layer. After successful creating a layer a next layer of powders is rolled on top of previous layers and fused together this process is repeated until the final 3D part is created (Figure 3d). The laser can only be used for powders with a low-melting/sintering temperature. Selective laser sintering (SLS) can be used for a variety of polymers, metals and alloy powders while selective laser melting (SLM) can only be used for certain metals such as steel and aluminium. After laser scanning in SLM, the powders are fully melted and fused together, which results in superior mechanical properties [17]. A detailed review of different materials and applications using SLM can be found in Ref. [18]. Scanning speed and Laser power are the main parameters affecting the sintering process. Different types of lasers and their effects on 3D printing can be found in Ref. [17]. High quality of printing and fine resolution are the maid advantages of PBF process.

The basic process of am

The first step of all additive manufacturing processes to create a digital geometric modeling (3D design) using AutoCAD, Pro-E etc. and then it is converted into (STL) file format, that is a standard input file format for almost all AM systems. The STL file is imported into specific software (Viscam by Marcam and Magics RP by Materialise), where it is pre-processed. If it is required a support structure and orientation in the model part it is created, optimum part orientation is selected and model is sliced at distances equal to the layer thickness.

This 3D design information electronically transmitted to the AM system. The AM system accept only standard (.STL) file format. The (.STL) file contain all the information about the model such as geometry, shape, size, colour and dimension. The physical part is fabricated layer by layer using one of the many currently available AM systems. After creating the physical part, the post-processing process is required to give final finish. The post processing activities includes removing the physical part, detaching the supports and sometime part requires minor cleaning and surface treatment operations to improve its appearance and strength [20]; Rapid Prototyping Primer [online].

Current state of the art

Technology Classification.

AM technologies that are capable of translating digital data into 3D physical object. The digital model data first converted into stereolithography (STL) file format then fed into an AM machine which fabricate real 3D object from (.STL) digital file format. One of the early approaches with similarities to AM processes, proposed by Ciraud in 1972, was essentially a powder deposition method using an energy beam [21]. After the significant research and development in the area of process, materials, equipment and software. AM has been used for fabricating model or prototyping parts for testing and visualization as well as to make tools, dies, and moulds. Now AM is also used for fabricating the functional end use products.

ASTM F42 committee, classified the AM processes into seven categories [22], All the processes differ from each other in their techniques used to deposit layers and the ways in which the deposited layers are bonded together.

Applications

Now a days, many industries such as automotive, aerospace, biomedical, energy, consumer goods, food engineering etc are motivated to adopt new manufacturing technology due to it lets the manufactures to fabricate complex shape objects without any tooling and fixture with no material wastage and less energy consumption. More application information can be found in related reports and papers [23-22].

Aerospace components often have complex geometries and it is usually made from advanced materials such as nickel superalloys, special steels, titanium alloys, which are difficult, time-consuming, and costly to manufacture using conventional processes. Additionally, aerospace production usually requires parts 1 to few thousand units. Therefore, AM are more suitable for aerospace part production for medium or low volume. For example, after manufacturing and testing of AM-fabricated parts, BAE Systems approved a replacement part made using AM a plastic window breather pipe for the BAE 146 regional jet [26].

In the automotive industry, it is used for making small quantities of structural and functional components, such as drive shafts, braking systems, engine exhausts and gear box components for luxury, low-volume vehicles.

The most beneficial field by AM is biomedical. Many parts such as custom-shaped orthopedic prostheses and implants, medical devices, cell printing, biological chips, tissue scaffolds, drug-screening models, living constructs, and surgical planning and training apparatuses can be effectively printed using AM. [27-29];

University–Industry Collaboration and Technology Transfer

Continuous efforts from AM developers and academic researchers, more and more companies have begun using AM technology to improve product performance, reduce time-to-market, reduce product manufacturing costs and increase product quality. Various AM processes have been introduced to the commercial market by industrial companies, including SLM Solutions in Germany, electrooptical systems (EOS), Arcam in Sweden and Reinshaw in the UK. Collaborative university and industry research in AM in the US have been initiated such as the Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) programs of most federal agencies. The major university–industry collaboration in AM currently supported by the US government in America.

Education and Training

Educating the general people about the AM empowers them about the technology and its utilization. Formal AM education has already been adopted by many university and college as curricula. Educational materials on rapid prototyping have long been a part of manufacturing engineering courses at many engineering colleges, and some classical manufacturing textbooks, such as Manufacturing Processes for Engineering Materials by Kalpak jian and Schmid [30]. Many universities and colleges are continuously conducting short term courses and conferences on AM to describe benefits and uses about the technology. Industrial managements also attempting to make their workers and employee skilful through the tanning programme.

In the age of the Internet, various online resources also provided for education and training to reach a much broader population [31]. It is expected that such an effort will encourage the integration of online design and collaboration tools with low-cost options for physical workspaces, where students and the general public alike may access educational support to gain practical, hands-on experiences.

FUTURE NEEDS

Technology Viewpoint.

AM have potential to build cost effective and complex geometry parts in any shapes and sizes ranging from nanometer to macro meter which is not possible easily in conventional methods. It uses a wide range of materials (metals, composites, polymers, ceramics, biomaterials and concretes)

Economy and Sustainability Viewpoint.
AM have many advantages over conventional manufacturing technique, it decreases the energy consumption, zero material wastage, shortened production time and shortened time to market which is less possible in conventional methods. In traditional manufacturing process specially in aerospace industries for example, large titanium blocks are machined to make a part which needs lots of energy and different tooling and also a huge material wastage which cannot be reuse. But in AM it can save the material wastage up to 90%, and energy consumption in making the same titanium component [32]. Moreover, this new Manufacturing tool enable manufacturer to adopt new product designs without the additional expenses of new physical tools associated with conventional processes.

Education and Training.
AM have the great potential for promoting science, technology and engineering. It can engage a broad population both students and adults. The availability of low-cost 3D printing equipment creates opportunities for population for hands-on labs in schools and colleges across the nation. These programs definitely will improve the skill in traditional engineering but also the biological sciences (molecular modeling), fashion design (clothing, footwear, and jewellery), medicine (orthopaedic implants and tissue engineering), interior design (space and facilities planning), and archaeology (bones and artifacts) [33].

Technology and Research.
AM is growing rapidly in the recent years but many challenges also need to be solved by research and development. These challenges are poor part accuracy caused by stair-stepping effect and residual stresses, support material once used cannot be reused etc. Limited material availability for AM needs more materials to be developed for AM uses. In order to AM-enabled “third industrial revolution,” the products must be fabricated efficiently, rapidly, and inexpensively while meeting with all the functional requirements. Continuous research and development are needed to explore the potential of 3D printing from rapid prototyping to the additive manufacture.

Materials.
More intensive materials need to be developed by research and development in order to broaden the selection of suitable materials, and needs to prepare a database among materials, process parameters and mechanical properties of parts fabricated by AM. It takes long time (nearly 10 years) In metallurgy to develop a new alloy, including the determination of various critical properties such as fatigue strength high mechanical strength and/or high corrosion

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resistance. The overall material development effort should be considering the future needs with desired rheological properties in order to create feature resolution on the order of sub-micro meters. The development of new biomaterials to serve as cell delivery media.

Design.

The most important features of AM which enhance the freedom of designers to explore novel application for this technology. First, various AM-oriented design tool needs to be developed such as conceptual design methods with help of designers in designing and exploring design spaces enabled by AM for the representations of property, process and shapes. Second, new user-friendly CAD systems should be re-invented to overcome the limitations of boundary representations, parametric and solid modeling in representing very complex geometries. Third, finite element analysis software must be developed to make use of simulation capabilities for primitive shapes, materials, material compositions, FGM, etc.

Advantages of am technologies

Some of the most important advantages of AM include:

1. Reduced lead time and cost: It reduces total part fabrication time almost 80% compared to conventional manufacturing methods due elimination of part coding and programming time and tool changing time.

2. Improved the quality of prototyping: The significant improvement in the surface quality and mechanical proprieties were noticed in compared to vacuum casting.

3. Parts with complex geometries: This new technology is capable to fabricate complex geometry part almost any geometry which is difficult in conventional methods.

4. No tools, moulds or punches are needed: AM is process which fabricate parts layer by layer direct from the CAD design without any tooling and fixture and without any human intervention.

MAJOR CHALLENGES

Still AM have some challenges which restrict its application in certain areas, these challenges are build time, accuracy, part orientation, build speed, pre-processing, material properties, postprocessing, system cost and. Some of the major challenges are listed in the available literature [34-37]. Some other listed here are:

1. Nonlinear behavior of AM fabricated parts. AM fabricated part show directionally dependent properties different in different directions as oppose to conventional manufacturing. Its shows higher mechanical properties for which parts fabricated in direction of layer.

2. The "stair-stepping" phenomenon. As the slicing layer is rectangular it cannot conform to curve surface across its entire thickness, as a result is affects surface quality and roughness. This phenomenon is known as the "stair-stepping" phenomenon.

3. Layer thickness selection. As we know that smaller layer thickness is better for better surface roughness and quality of product but smaller layer thickness requires more build time and lager data is required.

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This one is important parameters which need to be optimized.

4. Use of support structures. The support materials which uses during part manufacturing it is not recoverable or not useful for reuse. Sometime this support material affects the built part quality. It should me minimized by selecting suitable part orientation.

5. Direct manufacturing of metal parts. This is main challenge. This is main challenges existing now. The metal part produced from this technology still in comparation with conventionally manufactured parts. So, AM technology should be extended to build metal parts or prototypes with adequate strength and accuracy.

6. Development of new materials. Commonly used material in AM is paper, ceramics some metals and polymers. However, there are many interesting materials need to be developed such as biodegradable, aerospace materials, medical surgical tool materials etc.

7. AM system cost. Presently, additive manufacturing systems are very costly due to high performance cost and due to very less potential user. Increasing the no of potential user will decrease the installation and production cost.

So, what will be the future of this emerging technology, it can only be predicted by research and development.

CONCLUSION

AM is fast growing technology, initially it is knowing as rapid prototyping but in recent years general people calls it 3D printing. It processes layer by layer fabrication of the object direct from the model data. Using AM technology, it can be saved material wastage up to 40% as in oppose to subtractive manufacturing. AM technology are capable of producing end use products with high density and mechanical properties. It has seen a significant improvement in this technology in term of accuracy and material properties. Due to this it is most attractive technology in the industries such as aerospace, automotive, engineering, medical and food.

However, additive manufacturing requires more attention to improvement some issue such as high build time, porosity and high production cost. Due to this it prevents it’s uses in the industries because some industries required accuracy and high quality in minimum cost. So additive manufacturing is required continuous research and development to reduce cost, build time and material porosity.

However, the industries are looking toward the adoption of this technology because it enables easy fabrication of complicated geometries of any shape and size without any tooling while in subtractive manufacturing production it is difficult and time consuming also different tooling and fixture is required. So, AM is most suitable industries like aerospace and medical. AM technology still in its development stage and in coming years it will be a better solution to manufacturing industries. It requires research and development to overcome the challenges such a void formation between the layers of materials, porosity during the manufacturing process, which can reduce mechanical performance and anisotropic dependent behaviour. Some other issues such as transferring CAD data inaccuracies anddefects specially in curve surfaces due to the tessellation concept of CAD.

References

[1] Cheah, C.M., Chua, C.K., Lee, C.W., Feng, C. and Totong, K. (2005) “Rapid prototyping and tooling techniques: a review of applications for rapid investment casting”, International Journal of Advanced Manufacturing Technology, Vol. 25, No. 3-4, pp.308-320.

[2] Jee, H.J. And Sachs, E. (2000) “A visual simulation technique for 3D printing”, Advances in Engineering Software, Vol. 31, pp.97-106.

[3] Campbell, I., Bourell, D. and Gibson, I. (2012) “Additive manufacturing: rapid prototyping comes of age”, Rapid Prototyping Journal, Vol. 18, No. 4, pp.255-258.

[4] ASTM International (2012) “Standard terminology for additive manufacturing technologies: F2792-12a”, United States.

[5] Noorani, R. (2006) Rapid prototyping: principles & applications, John Wiley and Sons, Hoboken, New Jersey.

[6] Pham, D.T., Gault, R.S. (1998) “A comparison of rapid prototyping technologies”, International Journal of Machine Tools and Manufacture, Vol. 38, No. 10-11, pp.1257-1287.

[7] Yan, X. and Gu, P. (1997) “A review of rapid prototyping technologies and systems” Computer Aided Design, Vol. 28, No. 4, pp.307-318.

[8] Choi, S.H. and Samavedam, S. (2001) “Visualisation of rapid prototyping”, Rapid Prototyping Journal, Vol. 7, No. 2, pp.99-114.

[9] P. P. Kruth, (1991) “Material incress manufacturing by rapid prototyping techniques,” CIRP Annals Manufacturing Technology, vol. 40, no. 2, pp. 603–614.

[10] Lee, C.S., Kim, S.G., Kim, H.J. and Ahn, S.H. (2007). Measurement of anisotropic compressive strength of rapid prototyping parts. Journal of Materials Processing Technology, 187-188, 627-630.

[11] Liu, Q., Leu, M.C. and Schmitt, S.M. (2005). Rapid prototyping in dentistry: technology and application. International Journal of Advanced Manufacturing Technology, 29(3-4), 317-335.

[12] Zein, I., Hutmacher, D.W., Tan, K.C. and Teoh, S.H. (2002) “Fused deposition modeling of novel scaffold architectures for tissue engineering applications”, Biomaterials, Vol. 23, No. 4, pp.1169-1185.

[13] Wang X, Jiang M, Zhou Z, Gou J, Hui D. (2017) 3D printing of polymer matrix composites: a review and prospective. Compos B Eng, pp.442–58.

[14] Gibson, I., Rosen, D.W. and Stucker, B. (2010) Additive manufacturing technologies: Rapid prototyping to digital manufacturing, Springer, New York.

[15] Chockalingam, K., Jawahar, N., Chandrasekar, U. and Ramanathan, K.N. (2008) “Establishment of process model for part strength in stereolithography”, Journal

of Materials Processing Technology, Vol. 208, No. 1-3, pp.348-365.

[16] Zhou, J.G., Herscovici, D. and Chen, C.C. (2000) "Parametric process optimization to improve the accuracy of rapid prototyped stereolithography parts", International Journal of Machine Tools and Manufacture, Vol. 40, pp.363-379.

[17] Lee H, Lim CHJ, Low MJ, Tham N, Murukeshan VM, Kim Y-J. (2017) Lasers in additive manufacturing: a review. Int J Precis EngManuf-Green Technol 2017;4(3):307–22.

[18] Yap CY, Chua CK, Dong ZL, Liu ZH, Zhang DQ, Loh LE, Sing SL. (2015) Review of selective laser melting: materials and applications. Appl Phys Rev, pp.041101.

[19] Pandey, P.M., Reddy, N.V. and Dhande, S.G. (2003) "Slicing procedures in layered manufacturing: a review", Rapid Prototyping Journal, Vol. 9, No. 5, pp.274-288.

[20] Petrovic, V., Gonzalez, J.V.H., Fernando O.J., Gordillo, J.D., Puchades J.R.B. and Grinan, L.P. (2011) "Additive layered manufacturing: sectors of industrial application shown through case studies", International Journal of Production Research, Vol. 49, No. 4, pp.1061-1079.

[21] Bourell, D. L., Beaman, J. J., Leu, M. C., and Rosen, D. W., (2009), "A Brief History of Additive Manufacturing and the Roadmap for Additive Manufacturing: Looking Back and Looking Ahead," Processings of RapidTech, US-Turkey Workshop on Rapid Technologies, Istanbul, Turkey, Sept. 24-25, pp. 1-8.

[22] ASTM, (2009), ASTM International Committee F42 on Additive Manufacturing Technologies, ASTM F2792–10 Standard Terminology for Additive Manufacturing Technologies, ASTM, West Conshohocken, PA.

[23] Guo, N., and Leu, M. C., (2013), "Additive Manufacturing: Technology, Applications and Research Needs," Front. Mech. Eng., pp. 215–243.

[24] Bourell, D. L., Leu, M., and Rosen, D., (2009), Roadmap for Additive Manufacturing Identifying the Future of Freeform Processing, University of Texas, Austin, TX.

[25] Huang, Y., and Leu, M., (2014), Frontiers of Additive Manufacturing Research and Education, University of Florida, Gainesville, FL.

[26] Aviator.aero (Accessed Aug. 15, 2014) http://www.aviator.aero/press_releases/15570

[27] Ringeisen, B. R., Pirlo, R. K., Wu, P. K., Boland, T., Huang, Y., Sun, W., Hamid, Q., and Chrisey, D. B., (2013), "Cell and Organ Printing Turns 15: Diverse Research to Commercial Transitions," MRS Bull, pp. 834–843.

[28] Riggs, B. C., Dias, A. D., Schiele, N. R., Cristescu, R., Huang, Y., Corr, D. T., and Chrisey, D. B., 2011, "Matrix-Assisted Pulsed Laser Methods for Biofabrication," MRS Bull, pp. 1043–1050.

[29] Xu, C., Chai, W., Huang, Y., and Markwald, R. R., (2012), "Scaffold-Free Inkjet Printing of Three-Dimensional Zigzag Cellular Tubes," Biotechnol. Bioeng., 109(12), pp. 3152–3160.

[30] Kalpakjian, S., and Schmid, S. R., (2008), Manufacturing Processes for Engineering Materials, 5th ed., Prentice Hall, Upper Saddle River, NJ.

[31] Makerspace, http://makerspace.com/

[32] NIST, (2013), Measurement Science Roadmap for Metal-Based Additive Manufacturing, NIST, Gaithersburg, MD, http://events.energetics.com/nist-additivemfg/workshop/pdfs/nistadd_mfg_report_final.pdf

[33] Scott, J., Gupta, N., Weber, C., Newsome, S., Wohlers, T., and Caffrey, T., (2012), Additive Manufacturing: Status and Opportunities, Science and Technology Policy Institute, Washington, DC.

[34] Campbell, I., Bourell, D. and Gibson, I. (2012) “Additive manufacturing: rapid prototyping comes of age”, Rapid Prototyping Journal, Vol. 18, No. 4, pp.255-258.

[35] Kochan, D., Kai, C.C. and Zhaohui, D. (1999) “Rapid prototyping issues in the 21st century”, Computers in Industry, Vol. 39, No. 1, pp.3-10

[36] Onuh, S.O. and Yusuf Y.Y. (1999) “Rapid prototyping technology: applications and benefits for rapid product development”, Journal of Intelligent Manufacturing, Vol. 10, pp.301-311.

[37] Wong, K.V. and Hernandez, A. 2012. A Review of Additive Manufacturing. ISRN Mechanical Engineering, 2012, 1-10.

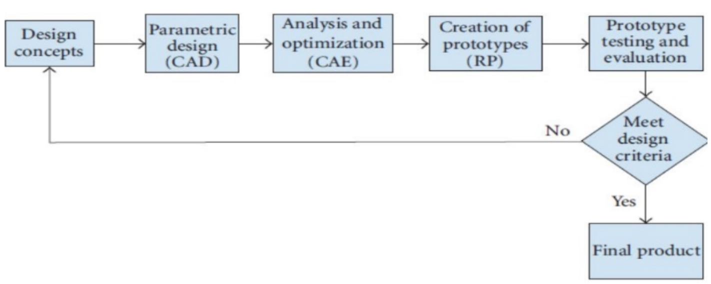

Figure 1: *Product development cycle [5].*

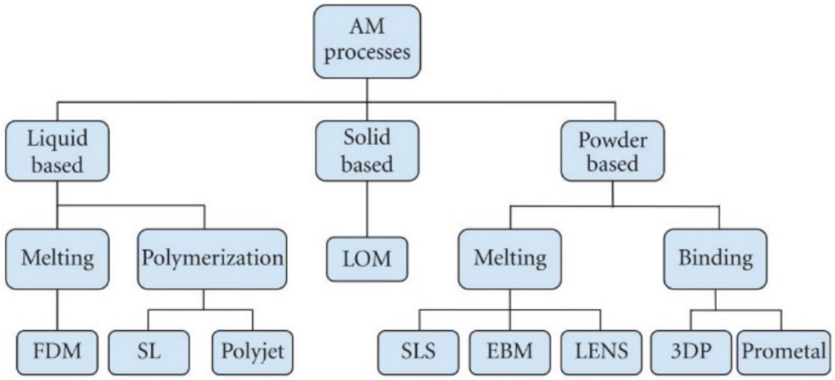

Figure 2: *Three-dimensional printing processes. [9].*

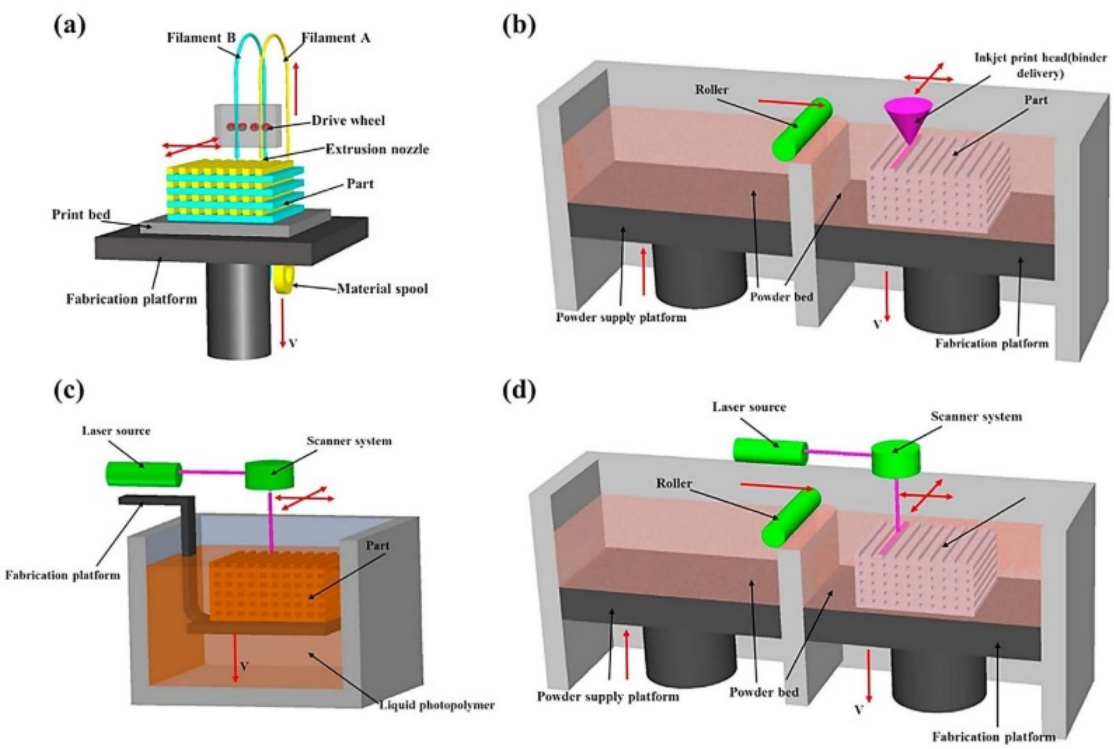

Figure 3: *Four main methods of AM: (a) FDM; (b) inkjet printing; (c) SL; (d) PBF [13].*

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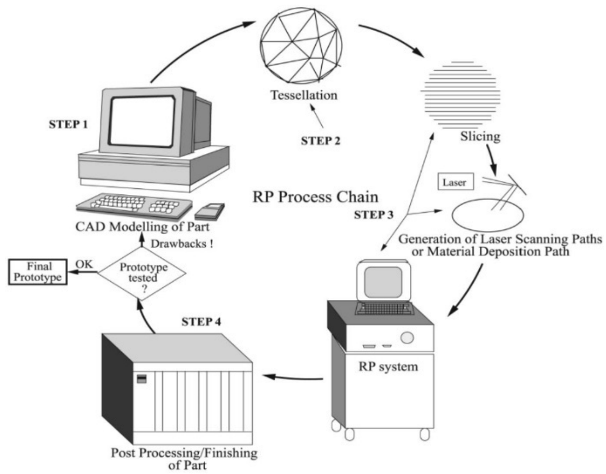

Figure 4: *Process chain involved in AM Processes [19].*

Table 1: *Applications, benefits and challenges of the main materials for AM.*

Materials	**Main Applications**	**Benefits**	**Challenges**
Metals and alloys	Automotive, Aerospace, Biomedical and Military	Mass-customisation, Multifunctional optimisation, Reduced material waste, Fewer assembly components	Dimensional inaccuracy and poor surface finish Post-processing may be required, Limited selection of alloys
Ceramics	Aerospace, Biomedical, Chemical industries and Automotive	Controlling porosity of lattices Printing complex structures and scaffolds for human body organs Reduced fabrication time.	Dimensional inaccuracy and poor surface finish Post-processing may be required Limited selection of 3D-printable ceramics
Polymers and composites	Automotive Aerospace Biomedical and Sports Medical	Fast prototyping Cost-effective Complex structures Mass-customisation	Limited selection of polymers and reinforcements Anisotropic mechanical properties. Weak mechanical properties