A study of additive manufacturing in the field of MEMS manufacturing

K. Hemaprasad*, S. Rahul

T. S. Srinivasan Centre for Polytechnic College and Advanced Training, Vanagaram, Chennai, India

Presented in National Conference on Micro System Technology (NCMST-2020), CMTI, March 4-6, 2020.

ABSTRACT

KEYWORDS

Additive Micro Fabrication,
Fabrication,
Micromachining,
Nano Finishing.

The recent success of additive manufacturing processes in the manufacturing sector has led to a shift in the focus from simple prototyping to real production-grade technology. Additive manufacturing is a relatively recent manufacturing method which has become a key area of interest in multiple industrial sectors. Deriving from CAD models the process can be used to create solid yet highly complex parts and pushes towards a tool-less manufacturing environment meaning improved quality and better efficiency in many cases. The enhanced capabilities of Additive Manufacturing processes to build intricate geometric shapes with high precision and resolution have led to their increased use in fabrication of Micro Electro Mechanical Systems (MEMS). The Additive Manufacturing technology has offered tremendous flexibility to users for fabricating custom - built components. Over the past few decades, different types of Additive Manufacturing technologies have been developed.

This article provides a comprehensive review of the recent developments and significant achievements in most widely used Additive Manufacturing technologies for MEMS fabrication, their working methodology, advantages, limitations, and potential applications. Furthermore, some of the emerging hybrid Additive Manufacturing technologies are discussed, and the current challenges associated with the Additive Manufacturing processes are addressed. Finally, future directions for process improvements in Additive Manufacturing techniques are presented.

1. Introduction

Additive Manufacturing (AM) is the process of joining materials to make objects from Computer Aided Design (CAD) model data, usually layer upon layer, as opposed to subtractive manufacturing methods. Additive manufacturing is also called 3D printing, additive fabrication, or freeform fabrication.

Additive manufacturing is a novel method of manufacturing parts directly from digital model by using layer by layer material build-up approach. This tool-less manufacturing method can produce fully dense metallic parts in short time, with high precision. Features of additive manufacturing like freedom of part design, part complexity, light weighting, part consolidation and design for function are garnering particular interests in metal additive manufacturing for aerospace, oil & gas, marine and automobile applications.

A computer-aided design (CAD) is created and exported to stereo lithography (STL) file format that is read by the AM equipment. There are many techniques available, which can be categorized according to their raw material. They are: (1) powder-based, (2) liquid-based, and (3) solid based. Some examples of powder-based techniques include selective laser melting (SLM), selective laser sintering (SLS), and electron beam melting (EBM). Liquid-based techniques include stereo lithography apparatus (SLA) and polyjet while solid-based techniques include laminated object manufacturing (LOM) and fused deposition modelling (FDM). The strengths of AM compared to conventional manufacturing methods are listed further. Basically, any material can be produced by one or another AM technique today. These materials can be divided into four main categories: plastics, metals, ceramics, and composites.

Today, a variety of plastics with vastly different mechanical, chemical & environmental properties can be additively manufactured, except for medized materials. Polyimides are a group of

*Corresponding author,
E-mail: hemaprasad.k@cpat.co.in

polymers with exceptionally high heat and chemical resistance that are yet to be used in AM. These materials vary in transparencies, thermal or mechanical properties. Polyamides are the most popular thermoplastics used in plastic laser sintering due to their wide spread use in injection moulding. However, the specific grades of polyamides used in AM have different physical properties and wider processing windows as compared to their injection moulding counterparts even though they are chemically identical.

The range of polymers used in AM encompasses thermoplastics, thermosets, elastomers, hydrogels, functional polymers, polymer blends, composites, and biological systems.

The most commonly used metals in AM are steel and its alloys due to their availability, reasonable cost, and biocompatibility as bone and dental implants. Titanium and its alloys are less commonly used followed by nickel, aluminium, copper, magnesium, cobalt-chrome, and tungsten. Crack-free metal matrix composites (MMC) of 99.9% density can be coupled with tungsten carbide-cobalt (WC-Co), ceramic or nonferrous reinforcements to enhance the mechanical properties. Such 3D printed composites are usually used in extreme environmental conditions, which include the oil and gas, mining, automotive, or power industry due to its high hardness and wear resistance. The uniform fine microstructure contributes to the increased hardness, eliminating any need for further improvements in mechanical properties through costly post-processing or heat treatment procedures.

2. Additive Manufacturing Processes

- Liquid Material Production
- Stereo lithography
- Digital Light Projection
- Frontal Polymerisation
- Screen Printing
- Inkjet Printing
- Direct Laser writing
- Powder Material Production
- Selective Laser Sintering / Melting
- Electron Beam Melting
- Gas Phase Deposition
- Solid Material Production
- Fused Deposition Modelling
- Sheet Lamination
- Advanced Additive Manufacturing Technologies
- Laser Induced Forward Transfer
- Electro Chemical Deposition

3. Laser Stereolithography

Laser scanner stereo lithography is the ancestor of all industrially offered additive manufacturing processes and is represented with 4500 installed systems worldwide (as of the end of 2006); after the extrusion machines, it has the most industrial Applications. The following section focuses on laser stereo lithography but Shows parallels to related processes where this seems appropriate.

Principle of Layer Generation

Laser stereo lithography is based on the point-wise solidification of photosensitive

Monomers (polymerization) using a laser scanning exposure apparatus (Galva scanner).

Stereo lithography machines utilizing the laser-scanner method consist of a container of liquid monomer, the installation space, which is usually also used as a reservoir, a construction platform, which is displaceable in the z direction in this container, and a laser-scanner unit, which writes the current layer information on the surface of

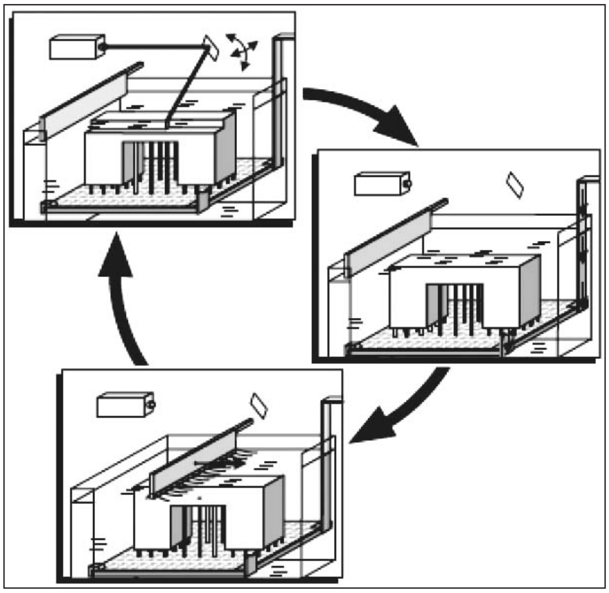

Fig. 1. Laser stereolithography.

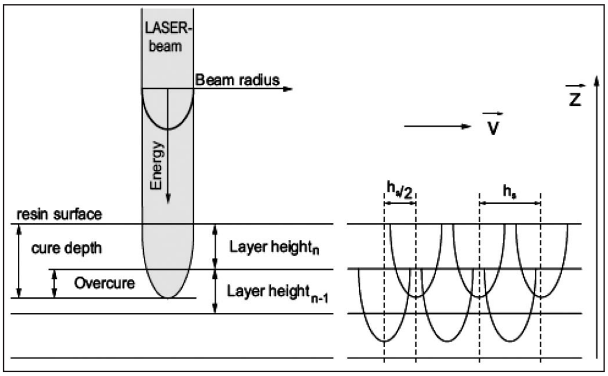

Fig. 2. Exposure to the laser beam on resin surface (A) Conditions in the single beam (B) Voxel structure.

the resin bath. The platform supports the part by support structures.

This allows for the production of overhangs, fixes unconnected parts of the model, and ensures the defined building up and subsequent removal of the construction platform. After solidification of a layer, the construction platform is lowered by one layer thickness. Thereafter, a new layer is applied (recoating), and this layer is exposed to the data of the new layer and thus solidified. Then, the process proceeds to the exposure of the following layers. In this way, the part “grows” in layers from bottom to top.

Stereo lithography processes try to realize the solidification of a layer with a row of single consolidations, so-called voxels. The geometry of the voxels is given by the energy distribution in the laser beam and the penetration characteristics of the resin. The ideal geometry has the shape of a parabolic of revolution. In order to achieve the necessary component strength, the laser penetrates both of the voxels in one layer and the two adjacent layers (“over cure”) so that the actual penetration depth of the laser is greater than the layer thickness (see Fig.2.). The generation of a layer and the tooting with the underlying previous layer takes place simultaneously.

4. Design/Construction

The basic structure of a laser stereo lithography machine is shown in Fig.3. The machine illustrated, a 3D Systems SLA-250, dates back to the year 1992. The machine is out of date in this design today, but very well suited to illustrate the basic design. The design principles as well as the essential components and their arrangement today determine the development of high-performance laser stereo lithography machines.

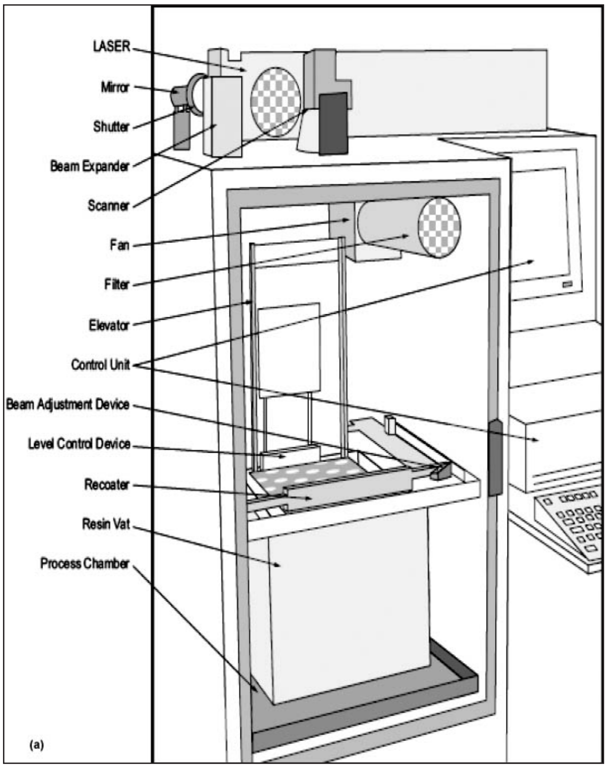

Fig. 3. The Basic structure of a laser stereo lithography machine.

The Viper SLA may be regarded as the successor. Its production has now Ceased. (For current machines, see Section 3.1.3, “Stereo lithography Apparatus (SLA), 3D Systems.”) Materials and consequently construction times and accuracies are machine and manufacturer-specific. Therefore, they are not described in general but are explained in the following sections in the course of the descriptions of each installation.

5. Postprocessing

The procedure of cleaning, removal of the supports, and post-cross-linking of the components is known as postprocessing and is the same for all laser-scanner-base stereolithography processes.

6. Selective Laser Sintering

In order to provide a baseline description of powder fusion processes, Selective Laser Sintering will be described as the paradigm approach to which the other powder bed fusion processes will be compared. As shown in Fig. 4., SLS fuses thin layers of powder (typically ~0.1 mm thick) which have been spread across the build area using a counter-rotating powder levelling roller.

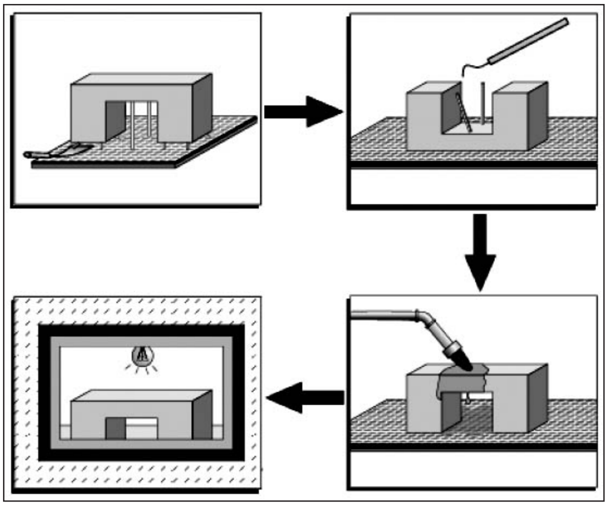

Fig. 4. Powder fusion processes.

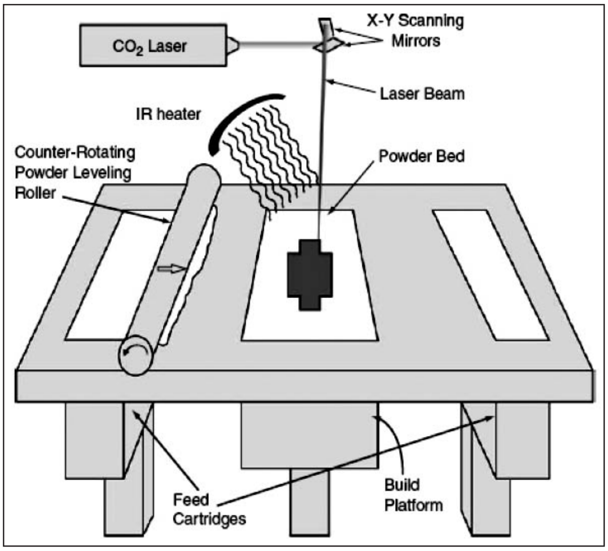

Fig. 5. Selective laser sintering.

The part building process takes place inside an enclosed chamber filled with nitrogen gas to minimize oxidation and degradation of the powdered material. The powder in the build platform is maintained at an elevated temperature just below the melting point and/or glass transition temperature of the powdered material. Infrared heaters are placed above the build platform to maintain an elevated temperature around the part being formed; as well as above the feed cartridges to pre-heat the powder prior to spreading over the build area. In some cases, the build platform is also heated using resistive heaters around the build platform. This pre-heating of powder and maintenance of an elevated, uniform temperature within the build platform is necessary to minimize the laser power requirements of the process (when pre-heating, less laser energy is required for fusion) and to prevent warping of the part during the build due to nonuniform thermal expansion and contraction (curling).

Once an appropriate powder layer has been formed and preheated, a focused CO2 laser beams directed on to the powder bed and is moved using galvanometers in such a way that it thermally fuses the material to form the slice cross-section. Surrounding powder remains loose and serves as support for subsequent layers, thus eliminating the need for the secondary supports which are necessary for photopolymer vat processes. After completing a layer, the build platform is lowered by one layer thickness and a new layer of powder is laid and levelled using the counter-rotating roller.

The beam scans the subsequent slice cross-section. This process repeats until the complete part is built. A cool-down period is typically required to allow the parts to uniformly come to a low-enough temperature that they can be handled and exposed to ambient temperature and atmosphere. If the parts and/or powder bed are prematurely exposed to ambient temperature and atmosphere, the powders may degrade in the presence of oxygen and parts may warp due to uneven thermal contraction. Finally, the parts are removed from the powder bed, loose powder is cleaned off the parts, and further finishing operations, if necessary, are performed.

7. Electron Beam Melting

Electron Beam Melting (EBM) has become a successful approach to PBF. In contrast to laser-based systems, EBM uses a high-energy electron beam to induce fusion between metal powder particles. This process was developed at Chalmers University of Technology, Sweden, and was commercialized by Arcana, Sweden in 2001. Similarly to SLM; in the EBM process, a focused electron beam scans across a thin layer of pre-laid powder, causing localized melting and solidification as per the slice cross-section.

However, there are a number of differences between how SLM and EBM are typically practiced. Since the source of energy in EBM is electrons, there are a number of differences between EBM and SLM which are inherent. Other differences, however, are due to engineering trade-offs as practiced in EBM and SLM and are not necessarily inherent to the processing.

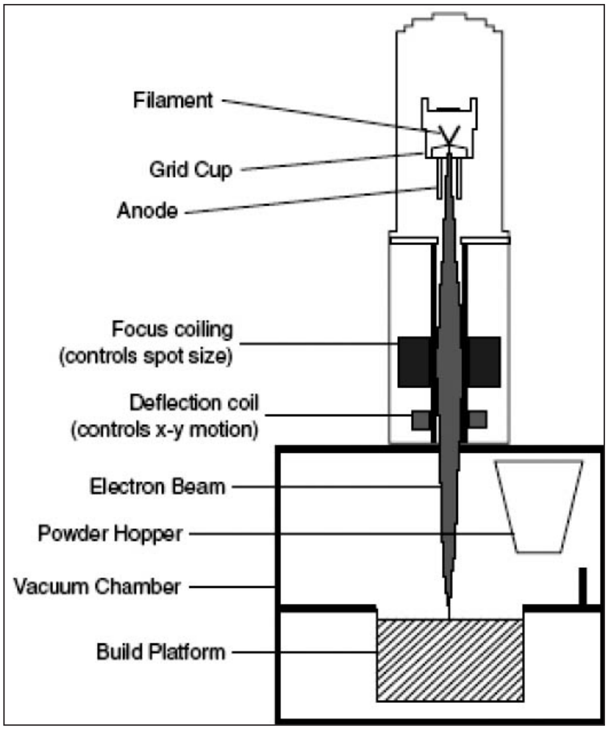

Fig. 6. Electron beam melting.

A schematic illustration of an EBM apparatus is shown as Fig.6.

Electron beams are inherently different from laser beams, as electron beams are made up of a stream of electrons moving near the speed of light, whereas, laser beams are made up of photons moving at the speed of light. When an electron beam is passed through a gas at atmospheric pressure, for instance, the electrons interact with the atoms in the gas and are deflected. In contrast, a laser beam can pass through a gas unaffected as long as the gas is transparent at the laser wavelength. Thus, EBM is practiced in a low-partial-pressure vacuum environment (a small amount of inert gas is swept through to remove gaseous by-products and oxygen), whereas SLM is practiced in an inert gas atmosphere at atmospheric pressure.

8. Conclusion

In the last years, Additive Manufacturing proved to be a powerful tool for rapid development of new products. In fact, Additive Manufacturing combines three main ideas: i) moving metrics from back to front, ii) involving from the design phase all specialists required for product development, and iii) taking into account the “customer voice”. The results are quite impressive: shortage of development time, less engineering changes, less time to market, higher quality & reliability.

MEMS seems to be a very appropriate field for Additive Manufacturing: multidisciplinary teams are needed, various sciences are involved, etc. The interest shown by many companies (including military ones) for a Additive Manufacturing approach in MEMS development is a clear sign about the future of Additive Manufacturing as a tool for MEMS research and manufacturing.

9. Reference

1. Ulsoy, A.G., & Warren, R.D. (1989). *Micro-computer application in manufacturing.* John Wiley & Sons.
2. Gibson, I., Rosen, D.W., & Stucker, B. (2010). *Additive manufacturing technologies.* Springer. Boston.
3. Gebhardt, A. (2012). *Understanding additive manufacturing.* Carl Hanser Verlag. Munich.

K. Hemaprasad is working currently as HoD, in Mechanical Engineering, T.S. Srinivasan Centre for Polytechnic College and Advanced Training, Chennai. He obtained his M.Tech from Dr. MGR University in 2011. He has 18 years of teaching experience. His specialisation includes CAD/CAM/CAE, CNC Programming & Machining, Process Planning, and Industrial Engineering. He presented 5 papers in National conferences and completed 8 NPTEL Courses in Total Quality Management, Ergonomics, Machining science, Operation Management, Train the Trainer etc., His Experiences includes designing multi skill training program, content development, skill training & assessment for industrial personnel etc.

S. Rahul is currently working in TS Srinivasan Centre for Polytechnic College and Advanced Training as a Lecturer. He is a graduate in Aeronautical Engineering from Karpagam Institute of technology Coimbatore. He has joined in Sri Narayana Guru Institute of Technology Adoor in June 2012 as Assistant Lecturer. In 2015 January he has joined in MAK controls and systems, Coimbatore as CI Testing Engineer. (E-mail: rahul@cpat.co.in)