# Recent Developments in Additive Manufacturing of Gears: A Review

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**Abstract.** Additive Layer Manufacturing (ALM) is an advanced technology to produce quality gears of metals and plastics. Some significant benefits such as capability to handle complex gear shapes and design, and produce near net-shaped gears; resource efficiency; and rapid product development etc. make this process a sustainable alternate to the other processes of gear manufacturing. This paper sheds light on the development of some of the important additive layer manufacturing processes such as Stereolithography, Fused Deposition Modeling, and 3D Printing to manufacture gears. The article aims to facilitate researchers and encourages them to do further research and development for improved gear quality, process productivity, and sustainability.

**Keywords.** Additive manufacturing; Gear; Miniaturization; Near net shape; Rapid prototyping

## 1. Introduction

Additive layer manufacturing (ALM) technology has complemented gear manufacturing industry with speed, quality, and versatility. To produce high quality gears at low cost is no more challenging after development of this technology. Scientific instruments, harmonic-drives, printers, robotic drives, domestic appliances, office machines, and electronic gadgets etc. are some of the application areas of ALM gears [1]. Since its inception in 1980 to till date, there has been a vast research and development in the field to exploit this technology for manufacturing of macro to micro engineered parts including gears. This technology follows a bottom-up approach to manufacture complex gear shapes of all types from their CAD shapes through layer by layer material deposition. Figure 1 depicts various steps followed by ALM based processes to manufacture gears. It starts with the preparation of CAD models of the gear to be produced followed by conversion of CAD model to STL file which is then transfer to the machine to build actual gear models [2].

Stereolithography, Fused Deposition Modeling, Selective Laser Sintering, and 3D Printing are some of the most extensively used ALM processes (See Fig. 2) to manufacture gears of various size and shapes from plastics, metal powders, composites and ceramics [3-5].

Benefits of additive manufacturing over conventional manufacturing are manifolds, such as:

- High quality and good surface integrity of gears
- Capability to produce metallic as well as non-metallic gears

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- Flexibility
- Less tooling and fixturing
- Resource and energy efficient
- On-demand production
- Less wastage
- Low environmental footprints due to short process chain and low emissions.

Moreover, a gear cutting hob of steel has also been successfully manufactured by additive manufacturing to machine powertrain gears [6].

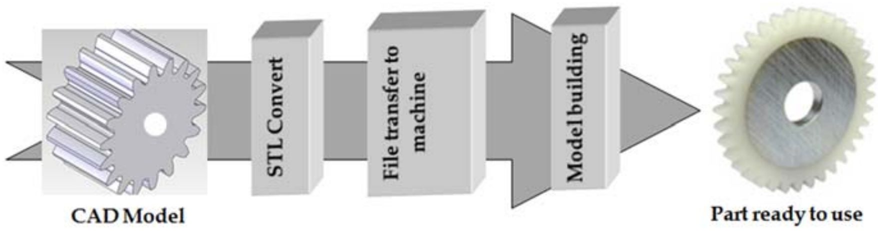


**Figure 1.** Steps in additive layer manufacturing of gears.

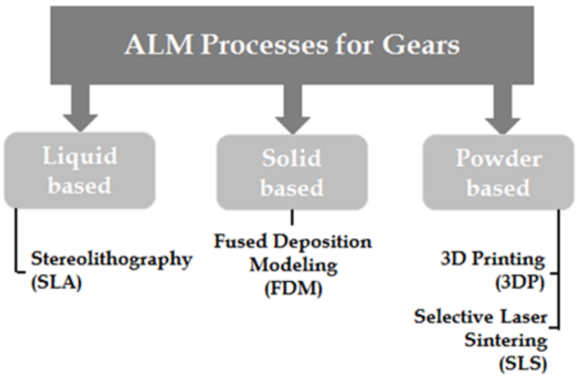


**Figure 2.** Additive layer manufacturing processes for gears.

The next section discusses the developments as regards to the accuracy and precision aspects in the aforementioned ALM processes to ensure the production of near net-shaped gears. The paper ends with a summary and scope of possible future research.

## 2. Developments in ALM Processes for Gear Manufactuirng

*2.1 Stereolithography*

Stereolithography was introduced in 1988. In this technique, liquid photo-curable polymers are used to manufacture gears [7]. A stereolithography machine consists of a build chamber filled with liquid resin, build platform movable in z direction, and a UV laser scanner unit. Figure 3 illustrates the working principle of stereolithography of a gear. A complete gear model is built by adequate joining of individual layers that are formed by conversion of liquid monomer to solid polymer under the action of UV laser beam. The formation of polymer layer is according to the 2D layer file of the solid 3D CAD model of the gear. As soon as one polymer layer is formed, the elevator moves down and a new layer of liquid monomer is exposed to be solidified and joined with the previously formed layer, and the cycle is repeated until the complete gear is made.

The positioning accuracy of the laser beam and the stability of the laser focus are major factors affecting the accuracy of stereolithography process.

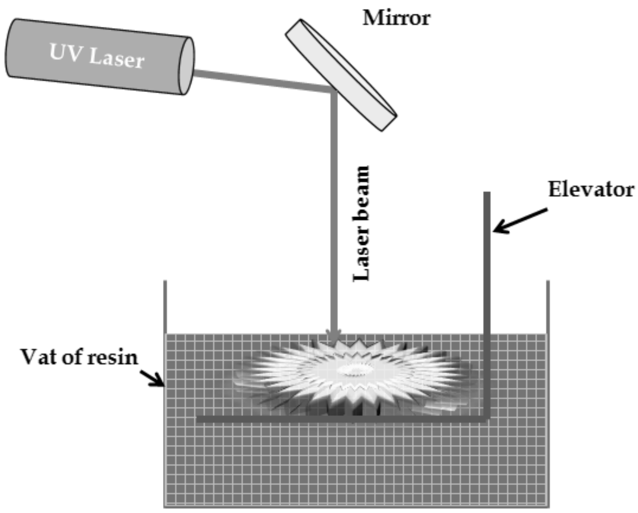


**Figure 3** Schematic of stereolothography of a gear [7].

Macro sized gears of polymers for various mechatronics applications especially speed reduction can be manufactured by stereolithography. With the use of stereolithography, Berger and Mäule (2009) manufactured high reduction polymer (epoxy resin) gears to be used in harmonic drives at low cost [8]. Budzik G (2011) successfully developed various gear shapes by stereolithography process (see Fig. 4) [1].

An abundant research work as regards to the development of micro version of stereolithography i.e. micro-stereolithography to produce micro and nano gears to be employed in MEMS-NEMS, micro-motors, bio-medical devices, and micro-robots has been done. Using an indigenously developed micro- stereolithography setup, Zhang et al. (1999) produced the polymer (silicon substrate) micro-gears of 100 µm and 400 µm diameters, and ceramic (alumina) micro-gears of 400 µm and 1000 µm diameters using laser power in the range 5-15 mW [4]. Using micro- stereolithography, Yoshinari et al. (2007) successfully developed micro-gears made of zirconia toughened alumina (ZTA) dispersed in acrylic resin. The manufactured gear possessed of excellent mechanical properties with 96.5% relative density, 26% average shrinkage ratio, and 14 GPa micro hardness [5].

**Figure 4** polymer resin gears manufactured by stereolithography (Source: From [1], published under CC BY 4.0 license, available from: http://dx.doi.org/10.5772/22848).

*2.2 Fused Deposition Modeling*

In fused deposition modeling (FDM), as shown in Fig 5, gear material in the form of metallic wire or plastic filament is heated and extruded layer by layer on a platform to build gear model [9, 10]. Acrylonitrile Butadiene Styrene, polyamide, and polycarbonate etc. are the main FDM material used for gear manufacturing. FDM manufactured gears are widely used in stepper motor planetary gear reducer, linear actuator, and positioning devices.

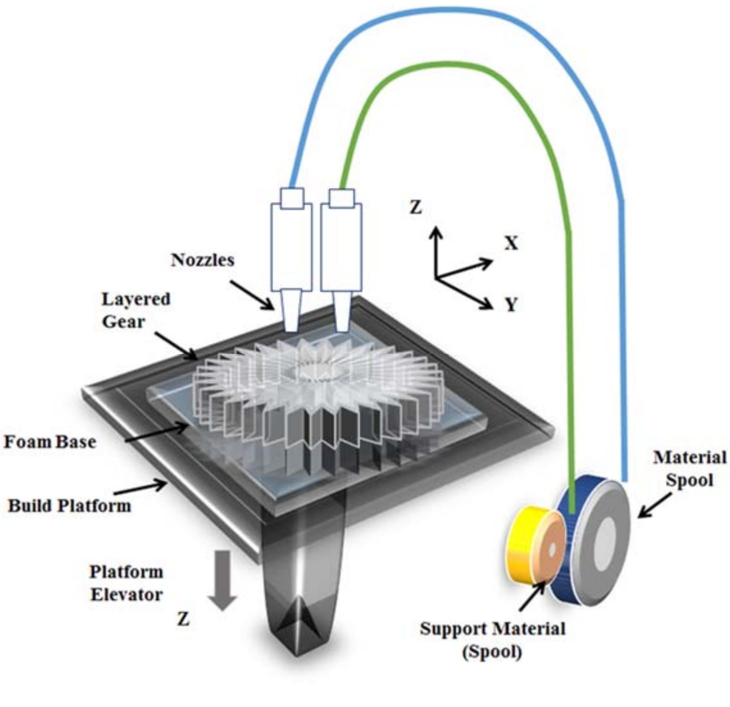


**Figure 5.** Working principle of gear manufacturing by fused deposition modeling.

*2.3 3D Printing*

3D printing works on the principle of injecting a binding agent through an inkjet head on the powdered layer to bind the particles in order to build the gear [7]. As shown in Fig.6, a 3D printing system comprises of a powder delivery system, inkjet head, working platform, and roller. A measured amount of powder is deposited on the working platform, and rolled with the help of roller. Thereafter, binder droplets are sprinkled on the prepared powder layer through the inkjet head that causes effective bonding of powder particles towards making individual layer. All the successive layers are formed by lowering the working platform until the complete gear is printed.

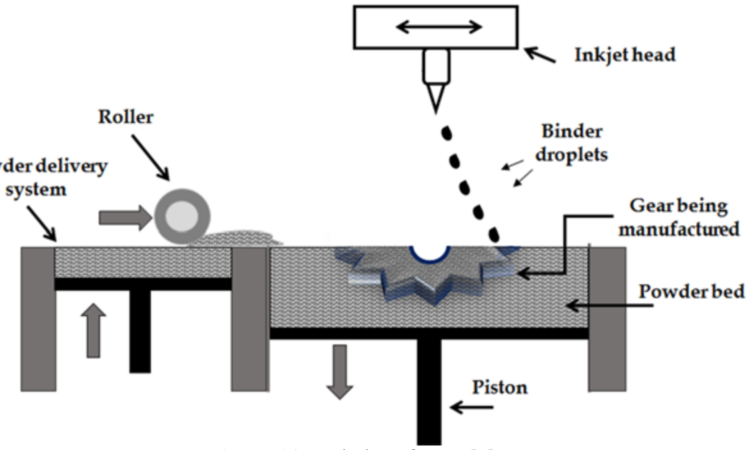


**Figure 6** 3D Printing of gears [7].

PolyJet printing is yet another 3D printing technology being used to manufacture gears. In gear building, the liquid photopolymer is jetted onto a build platform, which is then cured by UV light, and subsequently solidified [7]. Figure 7 illustrates the capability of 3D printing technique to manufacture variety of gears.


Figure 7. 3D printed gears (a) gear wheels, (b) gear wheel casting mould, (c) Al alloy casted gear made in the mould (Source: From [1], published under CC BY 4.0 license, available from: http://dx.doi.org/10.5772/22848).

## 3. Summary

Development in the ALM based techniques i.e. Stereolithography, Fused Deposition Modeling, and 3D Printing used for commercial manufacturing of micro, macro and prototype gears is discussed in this paper. Accuracy, precision, novel aspects, and comparison with conventional techniques are highlighted. A systematic review of the research conducted on manufacturing of gears by ALM is given. It hopes wider dissemination of these processes to manufacture high quality gears, and encourages researchers and engineers to conduct research and development in the area for improved gear quality, process productivity, and sustainability. The possible avenues for future research are as follows-

-Investigating in detail the effect of ALM parameters on surface quality of gears;
-Functional testing of ALM produced gears for noise, vibration, and wear analysis;
-More focused research on quality improvement of metal powder gears made by ALM processes.

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