SUPERPOSING OF THE ADDITIVE MANUFACTURING TECHNIQUES FOR INDUSTRIAL APPLICATIONS

A HOLISTIC REVIEW

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INTRODUCTION

Science is the most powerful key to overcome the problems with outrageous solutions in history. There are many examples in history but it accelerates after the First World War, in other words many countries have been accelerated and enhanced their scientific and defense investments. In 18^{th} century mechanical manufacturing of the machine equipment's especially after investigation of the steam engine; in 19^{th} century investigation of the automated machines using electricity especially investigating computer numerically controlled machines (CNC) and telephones; in 20^{th} century investigation of the computers in house fields; in this century autonomous machines, virtual environments, internet of things, transportation in cell scale, simulated enhanced reality, cyber security, big data and data mining, artificial intelligence and additive manufacturing are the main areas for fourth scientific revolutions. In this paper, additive manufacturing enhancements in a metallic and plastic applications, potentials and restrictions will be analyzed.

Gaining a revolution in industry and as an advanced manufacturing method, additive manufacturing technologies are raised. This technology opens the door for mass customization on-demand, simplifies complex assemblies and is capable of printing otherwise on multiple parts and applied on various industries namely aerospace, industrial, automotive, consumer products, medical technology.

In Figure 1, historical progress of the additive manufacturing is depicted. Most technology institutes are deeply worked on this subject recently and it is knowing that this subject is open to flourishment and change the historical manufacturing assets.

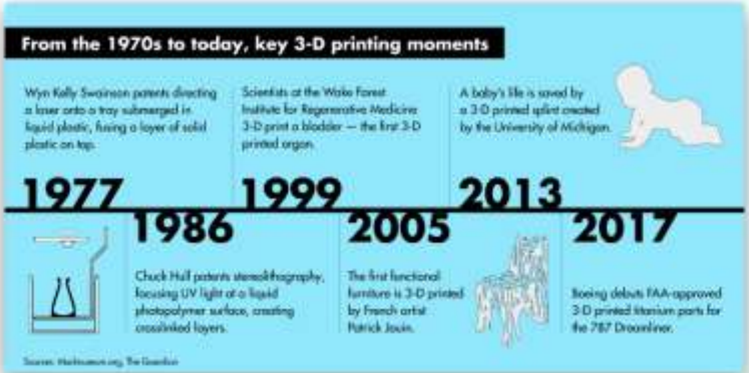


Figure 1 Time lined Progress of Additive Manufacturing [132]

Additive manufacturing technologies is a corner stone of the next industrial revolution which changes the normal in manufacturing areas in the field because of the fact that usual manufacturing process of a part of the machines based on the capabilities of processes basically machining, molding and casting and they needs a lot of investments of fix tools and equipment with very high skilled workforces. Additive manufacturing basically changes that, the on demanded parts using direct digital data for producing a machine part what is re-imaginable and re-designable of the designed product and re-evaluable and re-simulate of the performance of the product in same time. It is resulted in more efficient production and reduced time to market of the parts.

MAIN WORKFLOW FOR ADDITIVE MANUFACTURING

Additive manufacturing process begins with a concept or idea of the part or a product. It starts with a defined problem and needs to get a proper solution considering with functional requirements, aesthetic features, material constraints, intended additive manufacturing methods. Workflow starts with design phase and continues to file preparation, material preparation, process selection and post processes. Design phase includes Computer-Aided Design (CAD) data creation of three-dimensional model with preferred software such as Solidworks, AutoCAD or Fusion 360 with representing the geometry and dimensions of the object. Designers can exploit additive manufacturing ability for complex geometries, such as internal lattices or conformal cooling channels. Then Design for Additive Manufacturing (DfAM) process starts. DfAM process is mainly used for optimizing model especially additive manufacturing processes considering with minimizing supports and overhangs to reduce material and post-processing, using topology optimization to remove unnecessary materials, choosing built orientation to optimize strength and surface finish. [106, 107]. Additive manufacturing allows designers to create complex internal geometries not possible with traditional methods, like lattices that reduce weight without sacrificing strength. This model is optimized for minimal support use and improved mechanical performance.

File preparation process includes with conversion file to Standard Tessellation Language (STL) or newest ones is continued with file checking and repair processes then slicing operations. The CAD model is converted into a triangulated mesh file format usually STL or sometimes 3MF, OBJ or AMF. Exporting to STL or newest formats like 3MF which preserve more metadata and reduce errors with discretizing surfaces into triangles, finer tessellation increases file size but improves accuracy. File checking and repair state includes mesh repair and verifications with proper software such as Netfabb, MeshLab or Materialise Magic in order to ensure the file is printable. Detecting and repairing holes and gaps, fixing inverted normal, removing non-manifold edges and checking for intersecting triangles are some printability repairs. Before printing the files must be error-free. Software fixes holes or bad edges then slice model into thin layers. Supports are generated automatically or manually to hold overhangs during printing.

Slicing is another process; the repaired mesh is sliced into layers typically 20-100 microns thick into thin horizontal layers using slicer software. Cura, PrusaSlicer, Simplify3D, proprietary software and popular slicers for industrial additive manufacturing. Slicer software generates toolpath and G-codes. Set parameters are layer height, infill density and pattern (hexagonal, grid, gyroid), support structures locations, density and type, print speed and extrusion temperature. Figure 2 depicts in the mainframe of formation from the CAD data to slicing, after slicing G-codes generation happens and then production or printing begins. In latest studies the meshes in the STL files are studied as compliant or deformable.

Figure 2 Mainframe of data formation [110]

The process begins with the CAD model creation and then STL file preparation, in the middle slicing operations and layer slices takes place to define the tool path at the and producing as happened and 3D object is ready. The production process flow is given in the Figure 3 Production Process Flow in AM [132].

Figure 3 Production Process Flow in AM [132]

There are several materials could be selected as polymers such as Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Nylon, Polyether Ether Ketone (PEEK) or photopolymers or metallic ones such as stainless steel, titanium alloys, Inconel, aluminum, cobalt chromes etc. Details are given in the proceeding dedicated sections. Material conditioning and handling operation is another important feature. Drying filaments or powders to remove moisture to prevent defects is a conditioning of polymers. Mixing and blending composite materials, handling in inert atmospheres to avoid oxidation for metal powders is a conditioning of metal powders. Mixing and degassing photopolymer resins is preparing resign vat or powder bed conditioning. ASTM F42 standards are stand for these conditioning. The overall workflow is given in Figure 4. There are several real-world applications takes place with several important reasons. Tight tolerance of the complex geometries is one of them. Industrial metal additive manufacturing enables parts with internal lattices, conformal cooling channels and near-net shapes that are impossible to produce with casting or machining. Material and time saving are another one that powder reuse and nested builds reduce waste and cost, especially in expensive alloys like Ti6Al4V or Inconel. The last and most important one is range of applications that it is widely used in aerospace, rocket injections, medical implants, automotive tooling and defense components with critical properties. Space X Super Draco Engine combustion chamber and its injector printed in single piece using Direct Metal Laser Sintering (DMLS) from Inconel superalloy [108]. In this application there are various benefits namely enabled internal regeneration cooling channels, eliminating welding and joining operations. Produced parts are showed that superior strength, ductility, fracture resistance and lower variability compared to conventional casting or machining [108]. In operational conditions parts are stands for chamber pressure around thousand psi, withstanding extreme thermal stresses in flight. Production and lead time are dramatically reduced and minimal post-machining operation needed besides saving weight via complex internal geometry. The second example is UCSD TRI-D Rocket Engine, University of California, San Diego team built a liquid rocket engine via Direct Metal Laser Sintering (DMLS) using chromium-cobalt alloy powder. [109]. In this Project, post processing operations as removing supports and powder is done with ultrasonic cleaning, hardened and polished then tested on ground successfully. Korean Aerospace Research Institute – InssTek – Dual Material Nozzle (DED) is another example of high-tech applications. Al-bronze internal cooling channels produced with Inconel 625 shell as dual-material with 567 mm tall and 301 mm diameter large nozzle. It enables integrated multi-material thermal management, reduced assembly complexity and improved thermal performance.

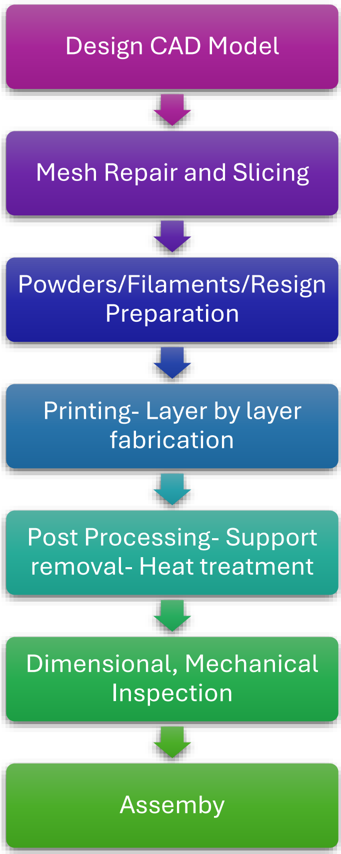


Figure 4 Whole production cycle for additive manufacturing

Additive manufacturing methods are defined in following section in details. Processes mainly worked with layer by layer fabrication approach using an energy supplier as laser or electron beam. Post processing phase includes part removal with the part is removed from the built platform and continues with supports, rafts or scaffolds removed with manually or chemically. Residual powder, uncured resign or debris is cleaned off. Parts are heated in controlled ovens to relieve residual stress. Hot Isostatic Pressing (HIP) densifies metal parts and removes the internal porosity. In surfaces qualification; sanding, bead blasting, polishing or coating for corrosion resistance methods mainly is used. Dimensional and mechanical inspection process is included to Coordinate Measuring Machines (CMM) or 3D laser scanners to verify tolerances. Tensile, fatigue, hardness testing is used for validating mechanical performances. X-ray Computed Tomography (CT), ultrasonic and dye penetrant testing are used for detect the internal defects known as Non-Destructive Testing (NDT) methods. Parts could be assembled into sub-systems and secondary machining operations (thread tapping or drilling) or joining operations could be placed. Final use in aerospace, automotive, medical implants or tooling purposes is monitoring for evaluating the performance for continuous improvement.

FUNDAMENTAL TECHNIQUES AND TECHNOLOGIES: PART- I METALLIC PARTS

This section includes additive manufacturing technologies used for the metallic parts and their compositions, mechanical properties of the printed parts surface qualities, possible future applications enhancements and problems are faced with are reviewed.

There are different methods of the additive manufacturing applied on the metallic parts. The most common ones are Powder Bed Fusion (PBF), Sheet Laminations (SL), Direct Energy Deposition (DED) and its sub new identified processes using metal wire filaments, for metallic materials [1, 2, 3, 7, 14, 15, 16, 17, 18]. Tabulated form of the additive manufacturing techniques for metal parts depicted in

Table 1

Table 1 Additive Manufacturing Techniques - Metal Parts. Metallic applications use wide variety of the metal and their compositions alloys but top rated in industry are mainly titanium, aluminum, stainless steel, zirconium, nickel and their alloys in the literature [2, 14, 16, 20]. Materials and advanced material compositions will be analyzed on the proceeding sections.

An overview of additive manufacturing technologies applied to metal materials, exploring the key techniques such as selective laser sintering (SLS), direct metal laser sintering (DMLS), and electron beam melting (EBM) [51], different processes involved in metal AM and examines the materials, challenges, and applications in various industries such as aerospace, automotive, and medical fields [52], selective laser melting (SLM) process, discussing the materials and challenges, along with a survey of its diverse applications in various industries [53].

Additionally, there are some advance techniques in literature, laser powder bed fusion (LPBF) processes, focusing on the parameters influencing material properties and its relationship with mechanical behavior and applications in aerospace and automotive sectors [54], development and processing of high-performance metal alloys for additive manufacturing, such as titanium and stainless steel, and their advanced applications [55], challenges and advancements in additive manufacturing of stainless steel, analyzing process-structure-property relationships, and application in industry [56], hybrid additive manufacturing techniques that combine additive manufacturing with subtractive processes (e.g., milling), enabling precision and material flexibility in the production of metal and polymer parts [57], additive manufacturing techniques that allow for the creation of hybrid materials (metal and plastic), offering new capabilities for producing functionally graded parts or structures with tailored properties [58].

Table 1 Additive Manufacturing Techniques - Metal Parts

Additive manufacturing technique	Sub-classification
Powder Bed Fusion (PBF)	Selective Laser Melting (SLM)
	Electron Beam Melting (EBM)
	Selective Laser Sintering (SLS)
Sheet Lamination (SL)	Selective Deposition Lamination (SDL)
	Laminated Object Manufacturing (LOM)
	Ultrasonic Additive Manufacturing (UAM)
Directed Energy Depositions (DED)	Laser Engineered Net Shaping (LENS)
	Blown Powder (BP)
	Direct Metal Deposition (DMD)
	Powder Fed Laser Melting (PFLM)
	Electron Beam Fused Filament (EBAM or EBFF)
	Laser Cladding (LC)

SLM technique is used for powder in a bed and laser is pointed on the selected area thermally bonded layer by layer on the powder bed [13]. Figure 5 depicted in the general overview and basic principles of the process. Fusion process could be happened with either tandem or four-pointed laser suppliers. Feeding rate, laser supply power, and closed loop powder control are the main important process factors [15, 16, 17]. Hence the process has advantages in problematic design shapes, refine microstructures, rapid cooling and good mechanical properties. Additionally, remained powder could be used for repetitive processes.

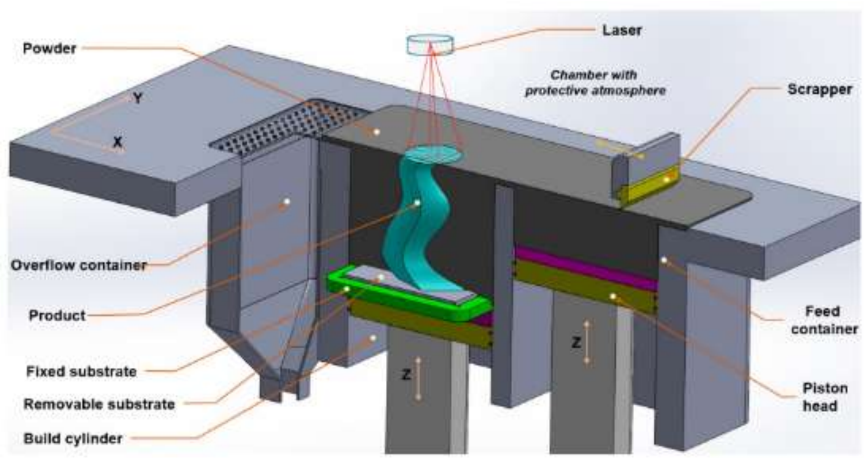


Figure 5 Selected Laser Beam Process [13]

Direct Metal Deposition (DMD) is another process for metal additive manufacturing. Spraying or ejected metal powder on a work station with a nozzle fused with laser supply with laser processing head [14], [15]. All processes are in a closed loop feedback controlled. Substrate powdered for each layer. Process parameters is similar with SLM process. Shielded gas, argon or helium is used for prevent the deposit from oxidation effects on the melting pool. End product could include some inhomogeneous microstructures and aggregations due to Heat Effected Zones (HEZ). In order to overcome such kind of issues holistic approach is studying to observe, track and control the process in a real time and change the process parameters simultaneously in the process. The process schematic is given in the Figure 6.

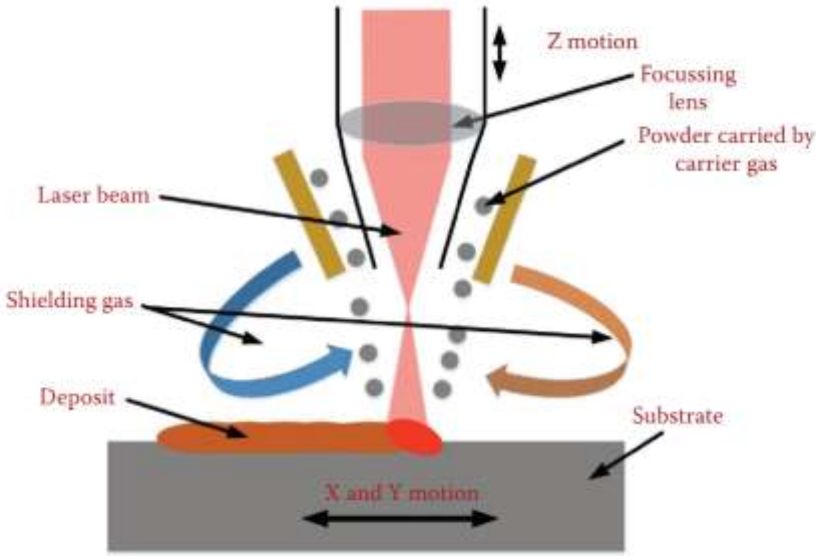


Figure 6 Powder based DMD with laser [18]

There are some re-defined processes for this method in literature namely Electron Beam Additive Manufacturing (EBAM), Wire Laser Additive Manufacturing (WLAM), Wire Arc Additive Manufacturing (WAAM) [1], [2]. EBAM is using electron beam gun but feeding with wire, molten alloy puddle lay out on the prior deposited layer on the substrate layer by layer, process is happened with vacuumed environment and costlier when comparing the other methods. The process schematic is depicted in the Figure 7. For WLAM, similarly wire feeder supplied on the building platform and laser beam is using for melting, the supplied wire optical and ultrasonic sensors are used for control the consistency of the layers to avoid porosity, cracks and delamination in real time closed feedback control systems. WAAM process is also using wire feeder but melting is happened with torch arc, molten pool is lay up on the previous layer on the component substrate. This last method could be likened to welding process but main differences are namely small-scale product build up, more precisions application method, controlled melting pool, better surface quality.

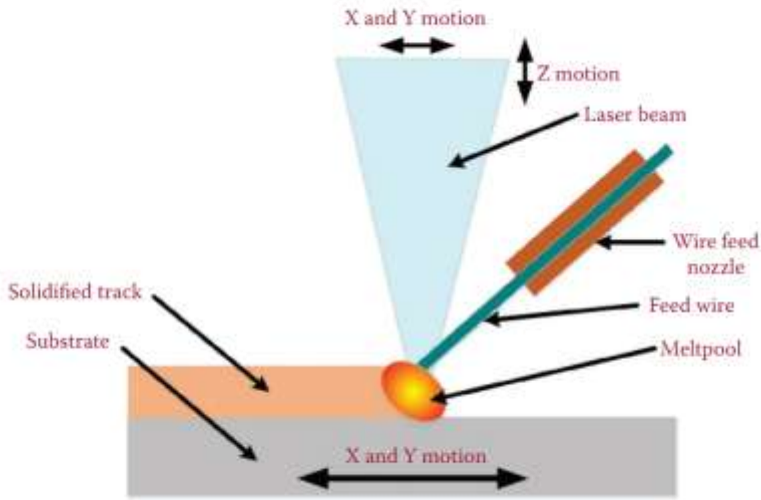


Figure 7 Wire feeder DMD with laser [18]

Electron Beam Melting method is another using method in additive manufacturing. This process is under vacuumed environment. Metal powder is melted with electron beam gun layer by layer. The process schematic is depicted in the Figure 8. Process parameters are beam power, beam feeding rate, powder thickness of a layer. Powder particle size is smaller and more precious quality than the other methods. Fluidic behavior of the powder is another important factor for this process. Surface quality, wear resistance, abrasion behavior is higher when comparing the other factors. Large scaled desired parts are quite difficult to manufacture with this method due to the obstacles of vacuumed environment.

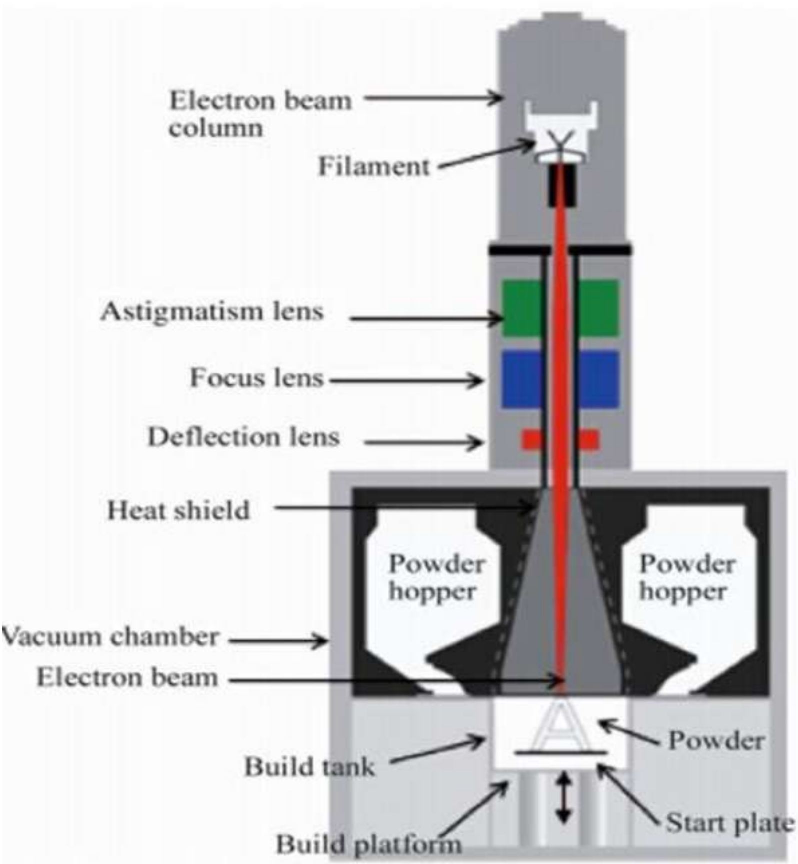


Figure 8 Electron Beam Melting (EBM) mechanism (Source: arcam.com)

Thermal spray 3D Printing (TS3DP) method is outranged method due to melting and spraying operation placed inside a gun, High Velocity Oxygen Fuel (HVOF) gun is feeding by continuous metal powder with a supersonic high velocity (600-1000 m/sec) and it melting before contacting with the substrate. The process schematic is depicted in the Figure 9. This method is advantageous to overcome the thermal residual stresses but it is not useful for oxygen reactive metals such as Zr or Ti.

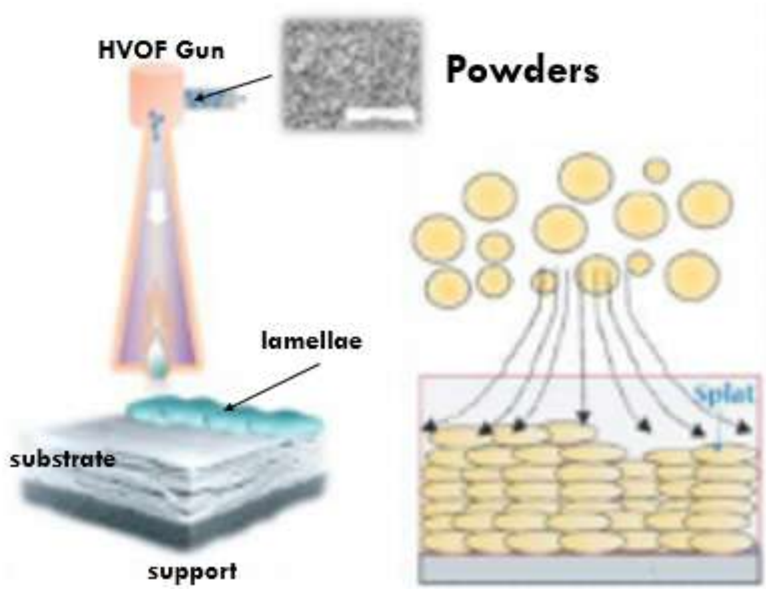


Figure 9 TS3DP method [1]

Selective Deposition Lamination (SDL) is a proprietary 3D printing process which builds part layer by layer using standard copy paper and each new layer is fixed to the previous layer using an adhesive. It results in that a much higher density of adhesive is deposited area producing the designed part and a much lower density of adhesive is applied in the surrounding area that will serve as the support structure. This process is rare application in area but it is useful for producing full colored 3D printing parts. Laminated Object Manufacturing (LOM) is using a sheet material and roller systems containing four rollers generally. In printing region there is a heated roller, laser, mirror and optics head, optics head manage the process dimensions which are generated from computer systems and make the cuts on the layered laminated sheet with directed laser energy. Heated roller is generally used on the laminated sheet in order to give the material isotropy and grain size effectiveness and efficiency. This process is a repetitive process in order to produce the desired designed product. Ultrasonic Additive Manufacturing (UAM) is basically a welding process and widely used in additive manufacturing areas. This process is used where in thin metal strips are welded in solid state on each other using ultrasounds to start the fabrication, the shape is programmed into the CNC machine and the strips are juxtaposed with a certain overlap ensuring a fully dense part. Vibration induced by ultrasound permit mechanical anchoring of the lamellae on the substrate thereafter lamellar stacked layer by layer. Materials can even be changed during the manufacturing to impart the special properties to the finished part and the process is used with incompatible materials because no liquid phase is formed during welding. After the welding, machining as a post process is performed in order to obtain the final part. Laser Engineered Net Shaping (LENS) is an additive manufacturing process in the directed energy deposition category and it uses powders sprayed into a laser to produce fully dense parts with a high deposition rate to begin a 3D drawing is imported into the devices software that divides part in multiple layers. The powder used is placed in a dispenser which ensures a constant flow during production and more than one type of powder can be used at the same time allowing the production parts with chemical composition gradients. The chamber of the system is flushed with argon gas in order to obtain an atmosphere containing a few Particle Per Minute (PPM) of oxygen and it is possible to work with reactive metals such as titanium and zirconium. This technique can also do part repair production of surface cladding and adding new sections to an existing part. Printing operation in part is taken few hours after a last step of surface machining as a post processing final part is obtained. Blown Powder (BP) is an additive manufacturing process and includes same characteristics with LENS. Material or powder is deposited from the nozzle and blown into the focal point of a high-power laser. The time saving process has a high deposition rates and has an ability to repair the damaged parts, creating relatively high dense parts comparing the other methods and good accuracy in built plane. Laser Cladding (LC) is another important application of the additive manufacturing. LC is an optimal technology for reconditioning of worn parts to prevent the corrosion. The process is carried out a numerically controlled robot. The heat effect is only one tenth comparing to traditional welding and LC requires no post-wealth heat treatment afterwards therefore laser cladding enables us to weld on high carbon steel components normally not accepted with classification societies or relevant. These authorities approve the laser cladding repairs case by case. LC is used powder or filament is specifically chosen for purpose for innovative repair solution for mechanical components and cost friendly alternative to total replacement of the components. Engine piston rings, turbocharger housing, crankshafts, pump plates, turbocharger shafts are some of the critical components repaired with this method. It is a fast and accurate method that requires no post-wealth treatment afterwards. Main advantages are reducing the delivery time and prolonging the service life of the critical components.

MATERIAL SELECTION FOR METALLIC APPLICATIONS

Stainless Steel (e.g., 316L, 17-4 PH), stainless steel alloys like 316L are known for good corrosion resistance and strength. 17-4 PH is a precipitation-hardened stainless steel with high strength and hardness, good general-purpose material, relatively easy to process, and strong performance under a wide range of conditions and aerospace, medical implants, automotive, and general industrial applications are application areas.

Titanium Alloys (e.g., Ti-6Al-4V), excellent strength-to-weight ratio, corrosion resistance, and biocompatibility are the main characteristics, ideal for lightweight, high-strength parts that need to perform in extreme conditions (like aerospace and medical implants), aerospace, medical implants, and high-performance engineering applications are the application areas. **Aerospace Applications:** Titanium is used in aerospace for structural components like aircraft frames, landing gear, and engine parts. It is valued for its light weight, strength, and resistance to extreme temperatures. **Medical Applications:** Titanium alloys are commonly used in medical implants such as hip replacements, dental implants, and orthopedic devices due to their biocompatibility, lightweight, and ability to resist corrosion in the body. **Advantages:** High strength-to-weight ratio, excellent corrosion resistance, biocompatible, good fatigue resistance, capable of high-temperature use. **Disadvantages:** Expensive, requires specialized metal 3D printers (e.g., powder bed fusion, electron beam melting).

Nickel Alloys (e.g., Inconel 625, Inconel 718), high strength, excellent resistance to heat and oxidation, and good corrosion resistance in harsh environments are the main characteristics, often used in high-performance applications like turbine blades, exhaust systems, and other components that face extreme temperatures, aerospace, power generation, and extreme heat environments are the application areas.

Inconel (Nickel-Chromium Alloy), Inconel is a family of high-performance superalloys made primarily of nickel and chromium. It is known for its excellent resistance to oxidation, corrosion, and high temperatures, making it ideal for extreme conditions. **Aerospace Applications:** Inconel is extensively used in aerospace for manufacturing turbine blades, exhaust nozzles, and other high-temperature components in jet engines. It can withstand temperatures up to 2,000°F (1,093°C) and is ideal for parts exposed to extreme thermal cycles. **Medical Applications:** Inconel is used in medical implants, particularly in orthopedic applications, due to its strength and biocompatibility. Exceptional high-temperature resistance, good strength at elevated temperatures, excellent corrosion resistance are advantages but expensive, difficult to 3D print (requires metal 3D printing techniques like Direct Metal Laser Sintering or Electron Beam Melting).

Ceramic Materials (e.g., Zirconia, Alumina), Ceramic materials used in AM, like zirconia (ZrO_2) and alumina (Al_2O_3), are known for their high hardness, wear resistance, and high-temperature stability. Ceramics also have exceptional electrical insulation properties. **Aerospace Applications:** Ceramics are used for thermal protection systems in aerospace, particularly for high-temperature insulating materials and components that can withstand extreme heat, such as turbine blades or heat shields**. Medical Applications:** Ceramics, especially zirconia, are commonly used in dental implants, as well as joint replacements (e.g., hip and knee implants) due to their hardness, wear resistance, and biocompatibility. **Advantages**: High hardness, wear resistance, high-temperature tolerance, electrical insulating properties, biocompatible. **Disadvantages**: Brittle nature, can be difficult to print due to the complexity of the material and the need for specialized equipment.

Aluminum Alloys (e.g., AlSi10Mg), lightweight, high strength-to-weight ratio, good thermal and electrical conductivity are properties and have advantages as popular in industries where weight reduction is crucial, especially for parts subjected to heat (like engine components), automotive, aerospace, and high-performance industrial parts are application areas.

Cobalt-Chromium Alloys, extremely strong, wear-resistant, and biocompatible, excellent for applications requiring high wear resistance and strength in medical and industrial contexts, medical implants, aerospace, and high-performance wear-resistant parts are application areas.

Tool Steels (e.g., H13, D2), hardness, wear resistance, and toughness are main characteristics, well-suited for applications that involve high mechanical stresses, including tooling and industrial parts, manufacturing tools, molds, dies, and automotive parts are main application areas.

Copper Alloys, excellent thermal and electrical conductivity, ideal for parts where heat dissipation or electrical conductivity is key factor as an advantage, electrical components, heat exchangers, and coils are the main application areas.

Precious Metals (e.g., Gold, Silver), corrosion resistance, ductility, and biocompatibility are the main characteristics, common in the manufacturing of intricate and high-value parts, Jewelry, high-end electronics, and medical devices are main application areas.

Application areas are the key factor for material selection and titanium and its alloys, copper and nickel-based superalloys, aluminum and its alloys are commonly used in aerospace sector. Selection criteria is their high strength to weight ratios, corrosion resistance and high temperature performances. Ti6Al4V (Grade 5), AlSi12Cu2Fe, AlSi10Mg, CuSn10 alloys are frequently studied ones in recent applications. Apart from the aerospace industry, tool steel, biomedical and implant application areas are main areas for additive manufactured products. Zirconium, beryllium, stainless steel, tungsten carbide, vanadium and many other metallic materials are in scope.

NONUNIFORMITY AND POST PROCESS

- Surface Finishing: Many AM parts require post-processing to achieve the desired surface quality. This could involve sanding, polishing, or coating to remove rough spots, layer lines, or visible support marks.
- Heat Treatment: For metal AM, parts often need to undergo heat treatment or annealing to relieve stresses and improve the material's mechanical properties. For plastics, processes like annealing or chemical smoothing can improve dimensional stability and strength.
- Resin or Powder Removal: In methods like SLA or SLS, the removal of residual material (such as excess resin or powder) is critical to achieving a high-quality part. This can require cleaning in solvents or media blasting.

Nonuniformity mainly resulted from the oxidation and multi phased thermal instabilities in melting. This effect is called as Heat Effected Zones (HEZ). There are many ongoing studies to underline this problem and to solve it. Holistic approach seems one of the solutions with a closed loop control of the melting process with high precision sensors and cameras and adapt the process parameters instantaneously to avoid the microcracks and inhomogeneous microstructures and aggregations. The paper focuses on the process optimization strategies in metal additive manufacturing, covering aspects such as laser power, scan speed, layer thickness, and how these parameters affect the final properties of parts [71].

These metallic processes defined in previous section have some disadvantages such as thermal and residual stresses, delamination and needs for end processes namely turning, milling and Hot Isostatic Pressing (HIP) [1], [18]. HIP process is a process to apply the external pressure on the part with a high temperature in order to compress the part and disappear the potential voids in the produced part. These voids are resulted from the inaccurate process parameters and resulted in porosity or delamination in the product lifecycle. In Figure 5, mentioned scrapper is used for refine and directionally homogenous distributed powder placement in some references it is called as roller and for scrap the remained powder in powder bed holder. There are many additional parameters for powder characterization in terms of metallurgical assets, shape and size of the particles, surface morphology, density, porosity, and flow properties [17].

COMPARISON OF THE METHODS

Selective Laser Melting (SLM) / Laser Powder Bed Fusion (LPBF), uses a high-powered laser to selectively melt fine metal powders layer by layer, commonly used for materials like titanium, stainless steel, aluminum, and cobalt-chrome alloys. High resolution and accuracy, can produce complex geometries and internal structures (e.g., lattice structures), good for aerospace, medical implants, and highly detailed components are main advantages. Slow build time, requires post-processing such as support removal, heat treatment, and surface finishing, expensive equipment and materials are main limitations. Aerospace components, medical implants, tooling, and custom parts are application areas.

Electron Beam Melting (EBM), uses an electron beam in a vacuum environment to melt metal powder layer by layer, typically used with titanium and its alloys, as well as some other high-performance metals. Good for high-temperature metals like titanium and cobalt-chrome alloys, faster than SLM due to higher energy densities, produces parts with good mechanical properties, especially in terms of strength are main advantages. Requires a vacuum chamber, which increases cost and complexity, surface finish quality may not be as fine as SLM; often requires post-processing, limited material options compared to SLM are limitations. Aerospace, medical implants, and highly demanding applications like high-performance turbine blades are application areas.

Direct Metal Laser Sintering (DMLS), very similar to SLM, but the terminology is often used for industrial machines in commercial production, uses a laser to fuse metal powders layer by layer. High precision and ability to create intricate designs, suitable for a wide range of metals, including stainless steel, titanium, and aluminum alloys are advantages. Similar to SLM, it has slow build times and the requirement for post-processing, expensive setup and material costs are limitations. Aerospace, automotive, medical industries for producing high-performance, complex parts are applications.

Metal Binder Jetting (MBJ), involves a binder material being jetted onto a metal powder bed layer by layer, which is then sintered (baked) in a furnace to create a solid part. Faster than powder-bed fusion methods (e.g., SLM and DMLS), lower material costs compared to other methods, can print parts with a wide variety of materials are main advantages. Limitations are parts produced are often porous and require post-sintering or infiltration with another metal (like bronze or copper) to improve strength, surface finish may require significant post-processing. Functional prototypes, casting patterns, and low-volume production of parts like tooling or automotive components are applications.

Directed Energy Deposition (DED), a nozzle or laser directs a stream of metal powder or wire onto a substrate, where it is melted by the heat source and deposited layer by layer, this method is sometimes referred to as Laser Metal Deposition (LMD) when using a laser. Advantages allows for repair and refurbishment of existing parts (e.g., turbine blades), can be used to build large parts or add material to existing ones, offers more material choices (metal wire or powder). Limitations are lower resolution and surface finish compared to powder-bed fusion methods, less control over part geometry than methods like SLM or DMLS. Repairing large components, aerospace, automotive, and tooling applications are application areas.

Metal Fused Deposition Modeling (FDM), similar to traditional FDM used with plastics, but with metal filaments or composite materials (metal powder mixed with plastic or wax), the filament is heated and extruded layer by layer to form the part. Advantages are relatively lower cost compared to other methods, work with larger parts due to the relatively low cost of machines, some processes can be used to create complex parts with minimal waste. Resolution is lower than SLM or DMLS, requires post-processing, including sintering, to remove the binder and fuse the metal powder, not suitable for high-performance, highly stressed parts are limitations. Rapid prototyping, low-cost production, and some functional parts in less demanding environments are application areas.

Selective Laser Sintering (SLS) – Non-metallic variants, although SLS is most commonly used with plastics, some machines are now capable of using metal powders mixed with polymer binders. Advantages are creation of complex geometries and detailed features, working at a faster pace than methods like SLM, more cost-effective in certain applications. Limitations are requiring sintering after printing, which can affect material properties, limited to low- and medium-strength parts for industrial applications. Often used for prototyping or production of parts where metal strength is not the primary concern.

As a comparison of the methods as a summary of the additive manufacturing technologies with different aspects as mentioned before is depicted in Table 2 Comparison of Additive Manufacturing Technologies.

Table 2 Comparison of Additive Manufacturing Technologies

Method	Materials	Precision	Speed	Post-Processing	Applications
SLM / LPBF	Titanium, stainless steel, aluminum	Very high	Slow	Extensive (support removal, heat treatment)	Aerospace, medical, tooling, automotive
EBM	Titanium, cobalt-chrome, others	High	Faster than SLM	Requires post-sintering	Aerospace, high-performance parts
DMLS	Stainless steel, titanium, alloys	Very high	Slow	Extensive (support removal)	Aerospace, automotive, medical, tooling
Metal Binder Jetting (MBJ)	Stainless steel, aluminum, copper	Medium	Fast	Significant post-sintering	Prototypes, tooling, casting patterns
DED	Titanium, steel, cobalt-chrome	Medium	Moderate	Moderate	Repair, aerospace, automotive, large parts
Metal FDM	Metal composite filaments	Low	Fast	Requires sintering	Prototyping, low-cost production

- SLM and DMLS are great for high-precision, complex, and highly functional parts but are slower and costlier.
- EBM offers faster build speeds and is excellent for high-performance materials like titanium but requires a vacuum chamber.
- Binder Jetting and FDM are cost-effective for prototyping or lower-performance applications but often require more post-processing.

- DED stands out for large parts, repairs, and material deposition but has lower resolution than powder-bed fusion methods.
- Choosing the right metallic AM method depends on factors like the required material properties, part size, resolution, speed, and cost.

POWDER PRODUCTION AND QUALIFICATION

Powder production methods are crucial for additive manufacturing (AM), especially for powder bed fusion, binder jetting, and direct energy deposition processes. The quality, particle size, shape, and purity of the powder directly influence the final part properties. An overview of the main powder production methods used for AM applications as explained as following.

Powder quality is a key bottleneck in additive manufacturing consistency and final part performance. The better the powder (spherical, narrow size, low contamination), the fewer defects and the higher the mechanical properties of the AM parts. Choosing the right powder production method aligned with your AM process and material requirements is critical.

GAS ATOMIZATION

Molten metal is poured through a nozzle and broken into fine droplets by a high-pressure gas stream (usually argon or nitrogen). These droplets rapidly solidify into spherical powder particles. Detailed explanation of the process is as molten metal is poured through a tundish into a nozzle and a high-pressure inert gas (argon or nitrogen) jet hits the molten metal stream, breaking it into fine droplets then droplets solidify while falling through a cooling chamber, forming powders. Powder is collected at the bottom or by cyclone separators. Characteristics of the powder mainly are spherical shape, good flowability, narrow particle size distribution. Quality of the powder could be labelled as following;

- Shape: Highly spherical, often near-perfect spheres.
- Size Distribution: Controllable, typically 15–100 µm.
- Surface Texture: Smooth surfaces, which improve flowability.
- Chemical Purity: High purity due to inert gas environment; minimal oxidation.
- Internal Defects: Minimal porosity inside powder particles.

Stainless steels, titanium alloys, nickel-based superalloys, aluminum alloys are most common materials and this method is widely used in additive manufacturing powder production. Pros of this production methods are that particles are excellent flowability and packing density for powder bed processes. Consistent particle size allows precise control of layer thickness. Good reproducibility for consistent part quality and suitable for high-value materials (Ti alloys, superalloys) characteristics are also common advantages of this process. On the other hand, high energy and capital cost, requiring inert atmosphere for reactive metals and some oversize or satellites form (small particles stuck on larger ones) are cons of this method. Figure 10 is depicted that the process of gas atomization, on the top a nozzle sets meets the melting process, vertical nozzle feeds the melted material and the gas nozzles are surrounded the melting nozzle in order to eject gas supplies towards the sprayed molten metal. Produced powders accumulated in the hoppers which are located at the bottom of the atomization chamber. This process enables various size range powders production in between from 50 µm and 150 µm [112]. Impacts on the additive manufacturing are spherical, flowable powder enables uniform layering and dense sintering/melting. Narrow size distribution reduces powder spreading issues. Critical for powder bed fusion (PBF) like SLM and EBM.

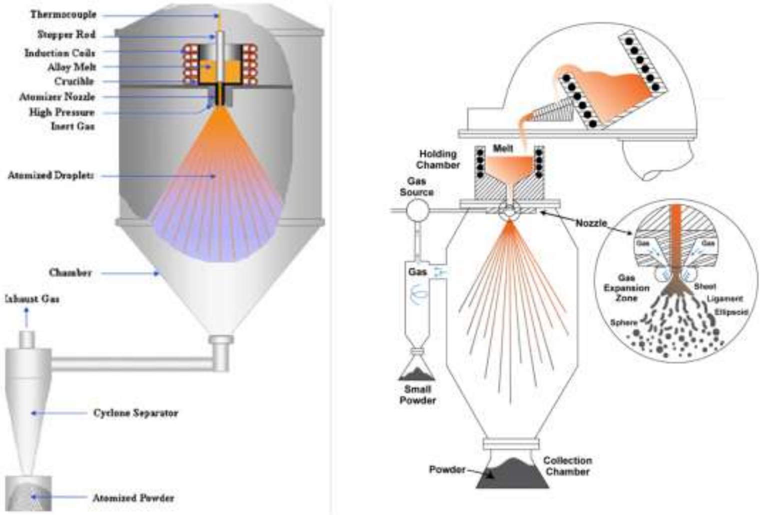


Figure 10 Gas Atomization Process [111]

WATER ATOMIZATION

In the water atomization process similar to gas atomization powder production process but it uses high-pressure water jets to break molten metal into particles. In details, molten metal stream is broken into droplets by high-pressure water jets. Rapid quenching leads to solidification. Typically produces irregular-shaped powders. Characteristics of the powder are irregular, angular particles with rough surfaces. Quality of the powder could be labelled as following;

- Shape: Irregular, angular, rough surfaces.
- Size Distribution: Wide distribution.
- Surface Texture: Rough, leading to poor flowability.
- Chemical Purity: Possible oxidation due to water interaction.

- Internal Defects: Sometimes porous or cracked particles.

This process is much lower cost compared to gas atomization. It is suitable for large-scale production of steels. Carbon steels, stainless steels are common used materials. Less common use in additive manufacturing due to irregular shapes and lower flowability, better for powder metallurgy or some additive manufacturing processes that tolerate irregular shapes. Poor flowability limits its use in fine powder AM processes. Surface oxidation and contamination and larger particle size variation causes inconsistent layer spreading. Figure 11 depicts the schematic of water atomization process with four stages; melting/pouring, atomization, solidification, and finally collection of metal powders. Stochiometric alloy are melted and then the melts are poured into the water atomization chamber using the nozzle. Meanwhile, the water is sprayed from the water jet at high pressure and then collides with the melts. The metal droplets are formed during the solidification and then the powders are collected. The final powder characteristics such as morphology, size, and shapes are controlled through various parameters including the melting temperature, nozzle diameter, water pressure, angle between the pouring of melts and water spray, etc.

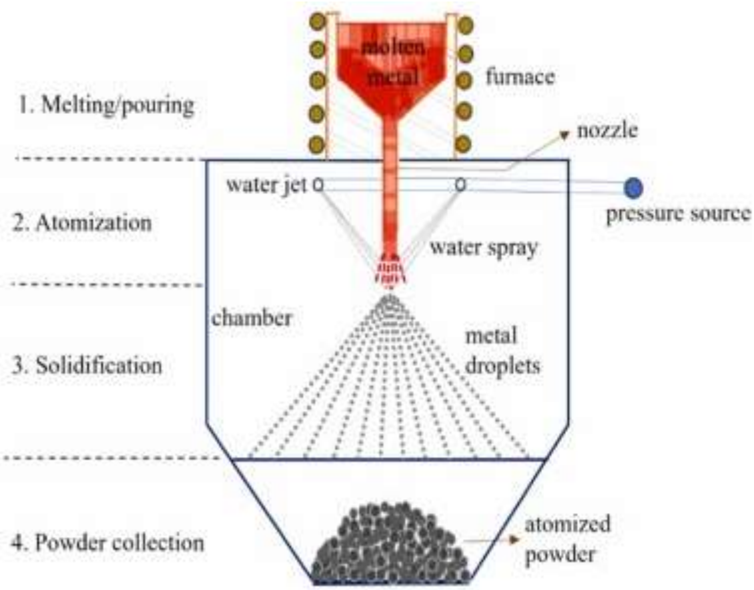


Figure 11 Schematic of water atomization (WA) process [113]

Impacts on the additive manufacturing are this method is typically used in less demanding additive manufacturing methods or where powder recycling isn't critical. In some cases, these produced powders are used for binder jetting or metal injection molding rather than powder bed fusion.

PLASMA ATOMIZATION

A wire feedstock is melted by a plasma arc and atomized into spherical particles. Details of the process is that wire feedstock is fed through a plasma torch, wire melts, droplets detach and solidify while falling. Produces very spherical and clean powders. Particles are extremely spherical, very clean and pure as a powder characteristic. Quality of the powder could be labelled as following;

- Shape: Nearly perfect spheres.
- Size Distribution: Narrow size control.

- Surface Texture: Smooth.
- Chemical Purity: Extremely high, reduced contamination.
- Internal Defects: Very low.

There are advantages of this process that are highest purity and sphericity, ideal for reactive metals like titanium and fine control over particle size. On the other hand, it is very expensive process and lower throughput than gas atomization. Titanium alloys are commonly used especially for aerospace applications. It has been highly recognized and adopted by General Electrical (GE) to produce powders for additive manufacturing, metal injection molding (MIM), hot and cold isostatic pressing (HIP & CIP) etc. Figure 12 (a)(b) shows the basic working principle of the plasma atomization process. Three converging supersonic plasma jets, which are generated by the non-transferred plasma torches, are employed for impinging and melting a metal wire and then atomizing the molten metal into metal droplets. Subsequently, the metal droplets are reformed into spherical shape by surface tension and solidify to powder form besides form it (c) depicts the illustration showing the three stages in the plasma atomization process.

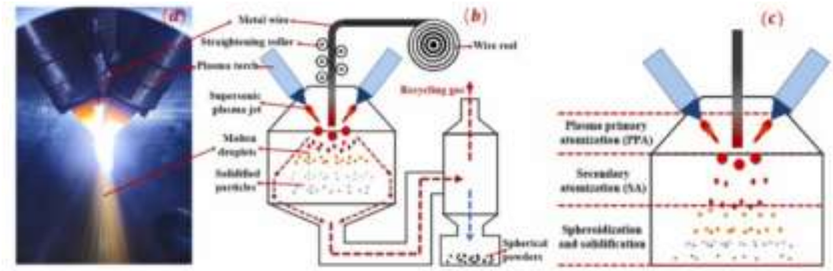


Figure 12 (a) Photo of the plasma atomization equipment; (b) Schematic illustration of the plasma atomization equipment; (c) Illustration showing the three stages in the plasma atomization process [114]

Possible impact analysis for additive manufacturing could be specified as it is used for aerospace-grade powders where purity and performance are critical and it enhances powder flow and layer uniformity in powder bed fusion.

MECHANICAL MILLING

Bulk metal is mechanically ground into fine powders using ball mills or attritors. Process is known as ball milling in literature as well. Details of the process is that bulk metal or alloy is ground into powder using rotating containers with milling balls. The process can be done under inert atmosphere or vacuum to avoid oxidation and sometimes used to produce alloy powders by mechanical alloying. Particle characteristics are mainly irregular shapes, wide size distribution, that are used for composite or alloy powders. Quality of the powder could be labelled as following;

- Shape: Irregular, often flaky or angular.
- Size Distribution: Broad.
- Surface Texture: Rough.
- Chemical Purity: Possible contamination from milling media.

- Internal Defects: High strain and defects within particles.

These powders commonly are used for hard-to-melt materials or composite powders. Advantages of this process are producing powders of materials difficult to melt, enabling alloying of immiscible metals, creating composite powders. Disadvantages are poor flowability limits use in powder bed processes, contamination risks, energy intensive. This process is less common due to poor flowability and used for specialized powder feedstock. Figure 13 depicts that principles of the ball milling method for reducing powder particle size.

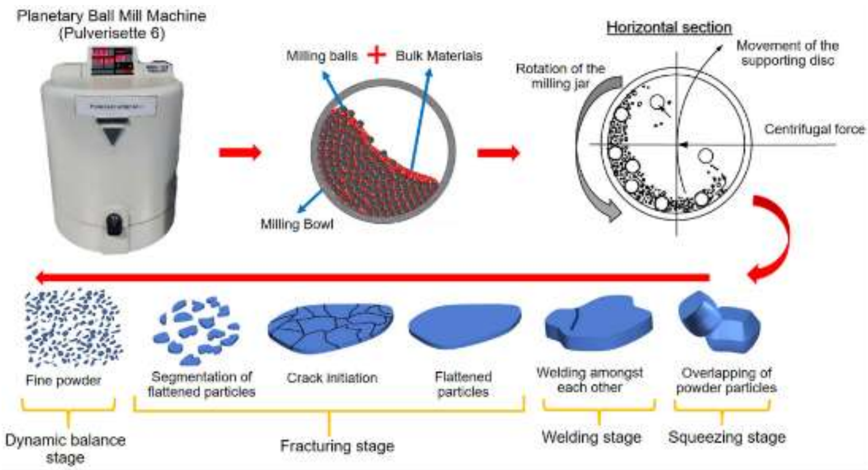


Figure 13 Schematics of mechanical milling [115]

Impact analysis of the method as follows; mostly used for special powders or research, rarely used in standard metal additive manufacturing due to flowability issues.

ELECTROLYSIS / CHEMICAL METHODS

It is a process that electrolytic deposition of metal powders or chemical reduction of metal salts to powder form. Detailed explanation of the process is that metal ions in solution are reduced by electrical current or chemical agents, powder forms by precipitation or deposition and lastly it requires washing, drying, and sometimes sintering to prepare powder. Characteristics of powder is fine with controlled chemistry. Quality of the powder could be labelled as following;

- Shape: Fine, can be spherical or irregular.
- Size Distribution: Very fine powders (<10 µm).
- Surface Texture: Fine, sometimes porous.
- Chemical Purity: High purity achievable.
- Internal Defects: Varies.

It is used for precious metals and specialty alloys. This process is good for specialty or precious metals (silver, gold) and produces very fine powders. Limited productions scale is resulted in specialized applications. Complex chemical handling, low production rates and not suitable for large scale metal AM powders are disadvantages. Figure 14 depicts that a general overview of the electrolysis and chemical methods and process of material compositions. This method is used for limited and niche applications in additive manufacturing.

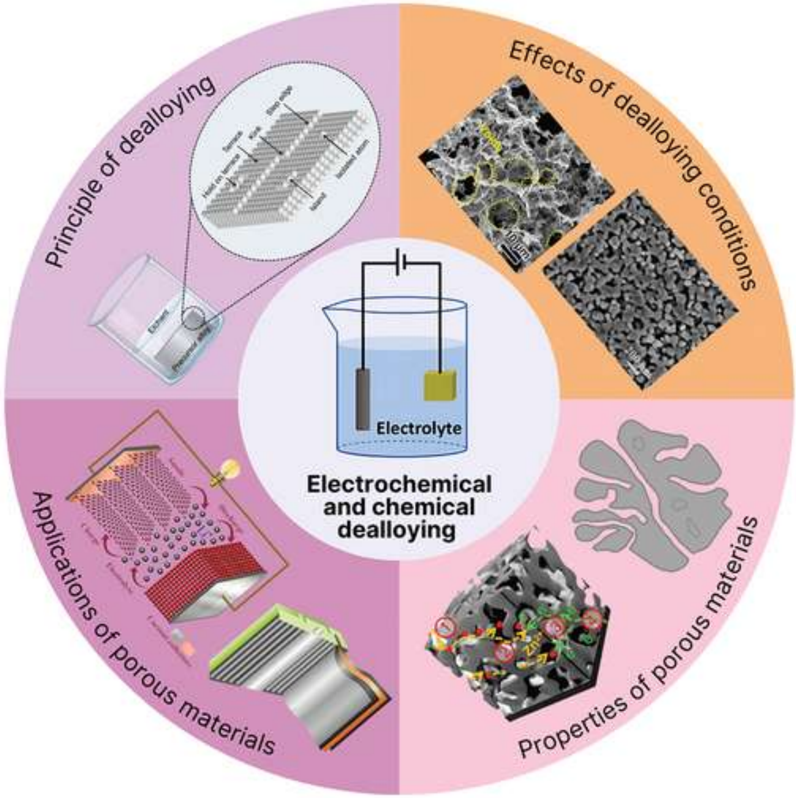


Figure 14 Electrochemical processes [116]

HYDRIDE-DEHYDRIDE (HDH) PROCESS

Metals like titanium are converted into hydrides, milled into powder, then dehydrogenated to obtain powder. More detailed explanation of this process is that bulk metal (usually titanium) is hydrogenated to form brittle hydrides then hydrides are milled into powder and lastly hydrogen is removed (dehydrogenation) to return to metal powder. Produced powders are irregular shapes particles. Quality of the powder could be labelled as following;

- Shape: Irregular, angular.

- Size Distribution: Variable, can be controlled by milling.
- Surface Texture: Rough.
- Chemical Purity: Can be high if processed carefully.
- Internal Defects: Some residual porosity.

Cheaper titanium powder production, uses less expensive raw materials and lower capital cost than atomization are advantages besides powder shape and flowability inferior to gas atomized powder and more challenging to use in powder bed fusion; better for DED or binder jetting are disadvantages. Commonly are used in titanium applications in cost-effective solutions. Figure 15 depicts that two common powder production methods which are gas atomization and Hydride-Dehydride (HDH) Process. Gas atomization including centrifugal atomization as a one-step process from raw to end-product. It generally suits for large-scale production for common metallic alloys, despite of the fact that it has lower control over the particle or sand size. On the other hand, in the HDH process, the material undergoes hydriding to form powder, dehydriding to convert the powder back to the original material composition, and then spheroidization to produce the high flowability spherical powder. HDH is well known for its ability to process material of various shapes and sizes, making it an ideal process for recycling waste that includes its own out-of-spec products.

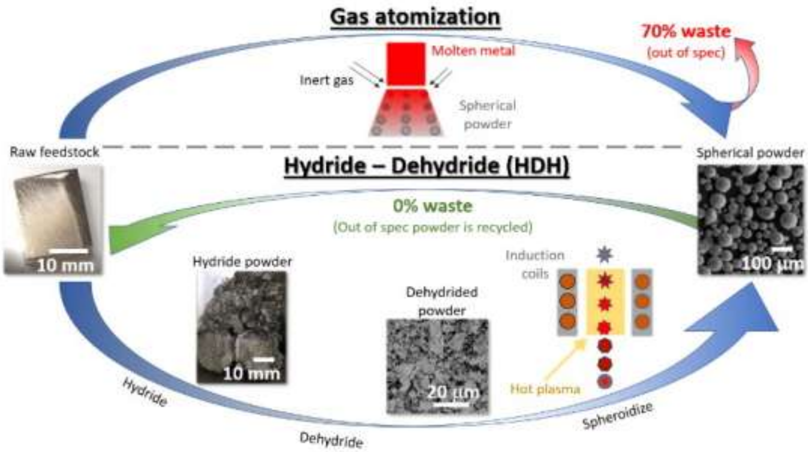


Figure 15 Two widely used powder production processes are atomization and Hydride-Dehydride (HDH) [117]

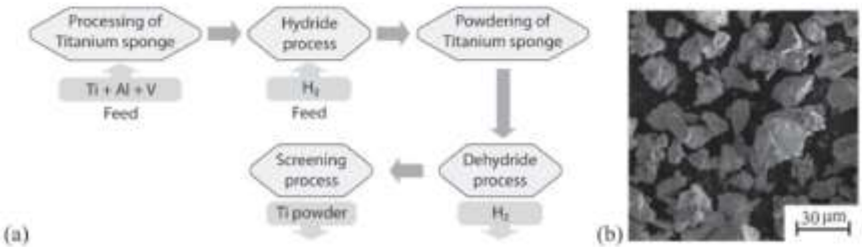


Figure 16 shows the process diagram of the event feeding materials and screening processes is important for this powder production cycle. Additionally, SEM image is also confirmed that the precise production.

Impacts on additive manufacturing are used for cost-effective titanium powders where high flowability is less critical and some companies developing HDH powders for additive manufacturing with tailored processing.

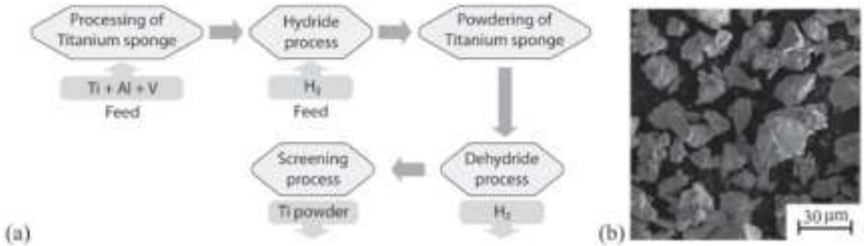


Figure 16 (a) Hydride-dehydride (HDH) process for the production of titanium powder. (b) SEM image [117]

COMPARISON OF THE POWDER PRODUCTION METHODS

As an overall comparison of the powder production methods are given with the Table 3 as following;

Table 3 Comparison of the Powder Production Methods

Method	Particle Shape	Particle Size Control	Typical Materials	AM Suitability
Gas Atomization	Spherical	Good	Ti, Ni alloys, steels	Excellent
Water Atomization	Irregular	Moderate	Steels	Limited
Plasma Atomization	Very spherical	Excellent	Ti alloys	High-end aerospace AM
Mechanical Milling	Irregular	Poor	Composites, hard alloys	Specialized use only
Electrolysis/Chem.	Fine, controlled	Good	Precious/specialty metals	Limited
Hydride-Dehydride	Irregular	Moderate	Titanium	Budget titanium powder

Particle shape and size are important feature in terms of spherical and uniform size improve flowability, packing density, and layer uniformity, surface chemistry is another feature for low oxidation and contamination prevent defects and poor melting.

Internal defects are important for dense particles avoid gas porosity in final parts and lastly size distribution reflects that narrow range improves layer deposition and part density.

POWDER CHARACTERISTICS ON AM PROCESSES

It is divided into spherical and irregular powders for particle shape characteristics. Spherical powders have excellent flowability, smooth and uniform spreading character in powder bed. This feature leads to dense layer and resulting in fever pores and better mechanical characteristics and it leads to predictable melting pool. On the other hand, irregular powders have poor flowability and it results in defects as voids or uneven melting areas. Irregular shapes have lower packing density in applications and it is also leading to porosity in parts. Irregular shapes have inconsistent melting behavior with variable energy absorption and it results in variable risks for incomplete fusion in process. In the production methods; selective laser melting and electron beam melting processes require spherical and very uniform powder. Binder jetting and direct energy disposition methods can tolerate somewhat irregular powders but still spherical powders and flowability characteristics preferred for uniformity.

For particle size and distribution characteristics; narrow size distribution facilitates uniform layer thickness with typically 20 to 50 micrometers. Narrow size improves packing density with fever voids and better mechanical properties. It reduces “satellite” particles such as small particles sticking to larger ones and improves flow and layer consistency. Wide size distribution characteristics; small particles fill gaps between the larger ones and it improves packing with controlled process but there is a risk for infilled regions as oxidation or poor flows. Different sizes increase the risk for powder spreading or dust explosions or inconsistent melting problems. Huge larger parts cause uneven layers. In additive manufacturing methods, selective laser melting tolerates 15 to 45 micrometers size distribution and direct energy distribution tolerates 45 to 145 micrometers size distribution. Binder jetting tolerates wider areas but sintering is a problematic area. Direct energy deposition process tolerates larger particles from 50 micrometers to 150 micrometers.

Another characteristic feature is surface morphology labelled as smooth and rough. Smooth surfaces enhance flowability with reducing inter-particle friction, improve powder bed spreading and lead to cleaner melt pools and fewer impurities. Besides, rough surfaces increase particle friction and cohesion which leads to poor flow and uneven layers, more surface area prone to oxidation or moisture absorption and this kind of surfaces could trap gas or contaminants and causing defects or porosity. In additive manufacturing powder bed processes selective laser melting and electron beam melting are very sensitive to surface morphology due to the need for uniform layers. Binder jetting powders must also flow well for binder saturation. Direct energy deposition less affected but still benefits from good powder flow.

Chemical composition is another feature for sand creation. Low oxygen, nitrogen, carbon content is critical for reactive metals like titanium and aluminum. It prevents formation of brittle oxides or nitrides in the final part, enhances mechanical properties and fatigue resistance. For high contamination and oxidation in chemical leads to inclusions and embrittlement, causes powder degradation over multiple reuse cycles, increases risk of defects like porosity, cracking, and reduced ductility. All additive manufacturing processes are affected from chemical composition. selective laser melting and electron beam melting are highly sensitive; even small increases in oxygen content degrade part quality. Binder jetting less reactive but impurities can affect sintering. Direct energy deposition also sensitive, especially for aerospace-grade materials.

MECHANICAL PROPERTIES EVALUATION

Many mechanical properties should be evaluated in a printed part which are namely density, melting point, specific heat tensile strength, modulus of elasticity, thermal conductivity, Brinell hardness, electrical resistivity are the major ones. An extensive review of the mechanical properties of metallic materials produced through additive manufacturing, including their strength, ductility, fatigue resistance, and post-processing techniques to enhance these properties [63].

Mechanical Properties:

Strength is a mechanical property with depending on the application, materials need to have sufficient tensile strength, yield strength, and fracture toughness. **Ductility** is the second property with some parts need to deform without fracturing (for instance, in automotive or aerospace applications). **Fatigue Resistance** is the third one with critical in applications where parts undergo repeated loading and unloading cycles. **Hardness** is the last and the hardness of a material affects its wear resistance, important for parts in harsh environments.

Thermal Properties:

Thermal Conductivity is important for applications involving heat dissipation, like in electronic components or engines. **Melting Point** is the second thermal property to determine the temperature at which the material can be used in additive manufacturing without deformation or degradation. **Thermal Expansion** is the last thermal property which affects the part's dimensional stability during post-processing steps like cooling or heat treatment.

Corrosion Resistance:

Some applications, especially in marine, medical, or chemical industries, require metals that can withstand corrosion or oxidation.

Printability:

Powder Flowability is the first factor in powder bed fusion AM methods (e.g., Selective Laser Melting, SLM), good powder flow properties are crucial for consistent printing. **Part Buildability** is the second one with some metals can be more challenging to print, leading to issues like warping or cracking, so a material's ease of use is an important consideration.

Post-Processing Requirements:

After the print, metals often require heat treatments, machining, or surface finishing. Some materials are easier to post-process than others, affecting the overall cost and time for part production.

Cost:

Metal powders can be expensive, and the cost of material influences both the feasibility and scale of production

MICROSTRUCTURAL CHARACTERISTICS IN METALLIC AM

Additive manufacturing (AM), or 3D printing, of metallic materials is increasingly popular due to its ability to produce complex geometries that are difficult or impossible to achieve with traditional manufacturing methods. However, one of the most significant factors affecting the performance of AM components is their microstructure, which is influenced by the specific AM technique, the material being processed, and the parameters used during printing. Below is a more detailed exploration of the microstructures of metallic AM, with a focus on common techniques like Laser Powder Bed Fusion (LPBF), Electron Beam Melting (EBM), and Direct Metal Laser Sintering (DMLS) [95, 96, 98, 100, 103, 104]. Melting formation mechanism of the powder based additive manufacturing process is shown in Figure 17.

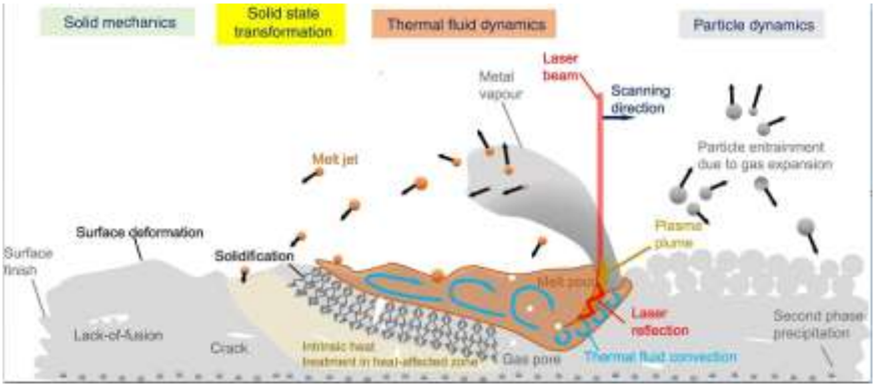


Figure 17 Melting and formation mechanism for SLM [96]

MICROSTRUCTURAL CHARACTERISTICS

GRAIN STRUCTURE

In metallic AM, the rapid cooling rates and high thermal gradients during processing cause significant differences in the grain structure compared to traditional processes like casting or forging. The grain size and shape are highly dependent on the cooling rates, with AM typically producing fine-grained microstructures. Key characteristics include:

- **Fine Equiaxed Grains**: The fast cooling in AM processes like LPBF leads to the nucleation of many grains in a short period. This rapid cooling creates a fine, equiaxed grain structure, which is typically desirable as it can improve the material's mechanical properties, such as strength and fatigue resistance. However, this fine grain structure can also lead to increased residual stresses in the material.

- **Columnar Grains**: In some cases, particularly in parts that experience slower cooling or certain alloys, columnar grains can form. These elongated grains are typically observed in the build direction and can result in anisotropic mechanical properties, where the material behaves differently in the vertical (build) direction compared to the horizontal direction.
- **Grain Refinement**: For materials like stainless steel, titanium alloys, and superalloys, grain refinement is often observed due to the rapid solidification and the localized heating during layer-by-layer deposition. For example, in ultrasound-assisted AM of 316L stainless steel, grain refinement occurs due to enhanced nucleation during solidification [94, 95, 99].

Grain formation is directly affected on the layer composition, and is resulted from many parameters including building direction and thermal inputs of the system. Figure 18 is a visual demonstration of the grain formation and binary systems.

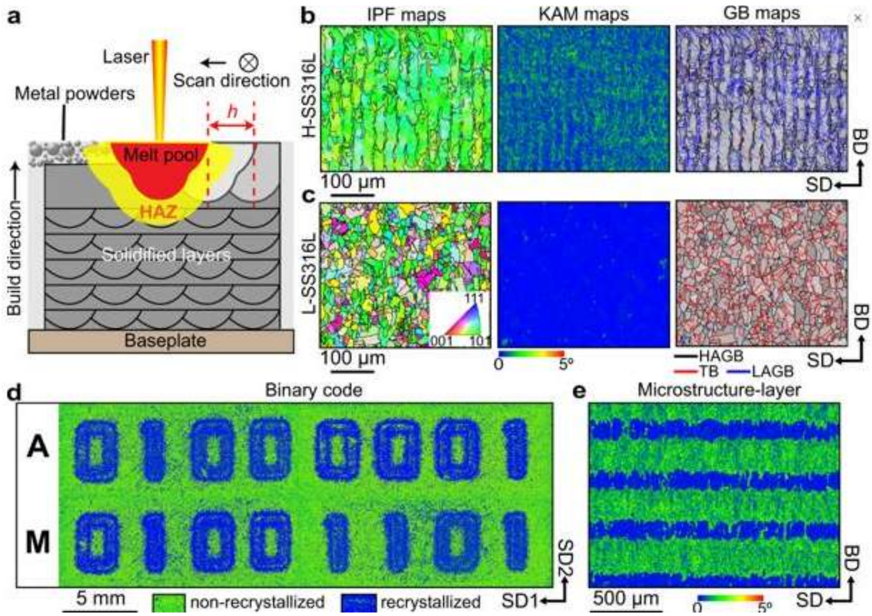


Figure 18 Grain formation analysis [94,95,99]

PHASE COMPOSITION

The phase composition in AM materials is strongly influenced by the cooling rate and thermal gradients during processing. Rapid cooling can suppress the formation of equilibrium phases, leading to the development of non-equilibrium phases that might not be present in conventionally processed materials.

- **Inconel 625 and DMLS**: For high-performance alloys such as Inconel 625, processed using DMLS, high thermal gradients lead to a rapid solidification rate, which results in unique microstructures. This often includes a mix of gamma (γ) and gamma prime (γ') phases, which can form during solidification and solid-state cooling [93].

- **Titanium Alloys**: In titanium alloys like Ti-6Al-4V, phase transitions between the alpha (α) and beta (β) phases occur due to the cooling history. The fast cooling rates of AM processes can lead to a predominantly alpha-phase microstructure, which has different mechanical properties from the mixed α/β phase typically found in cast or wrought Ti-6Al-4V [101, 102, 104].

TEXTURE AND ANISOTROPY

AM processes produce components layer-by-layer, and the build direction plays a crucial role in determining the final texture and mechanical anisotropy of the material.

- **Layer-by-Layer Deposition**: The anisotropy arises because the microstructure is heavily dependent on the deposition direction. In LPBF, the melt pool solidifies in a certain direction, creating a strong directional texture. This can lead to different mechanical properties in the build direction compared to the horizontal or transverse directions. Figure 19 shows that layer by layer deposition creates some anisotropic formations and this leads to the mechanical behavior differentiation in application [93].

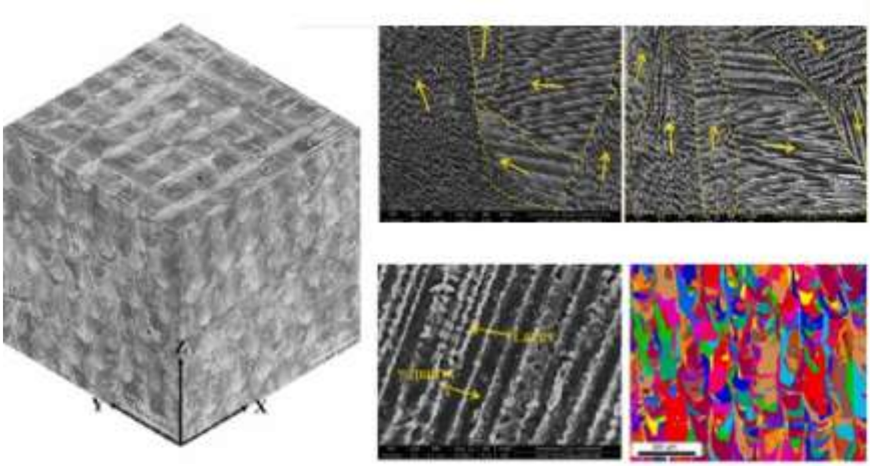


Figure 19 Anisotropic formation [93]

- **Example in Ti-6Al-4V**: The texture of Ti-6Al-4V produced via LPBF results in a preferred crystallographic orientation along the build direction, which influences the material's tensile strength, fatigue behavior, and crack propagation. The mechanical properties are generally weaker along the build direction due to this anisotropy [102].

PROCESS-STRUCTURE-PROPERTY RELATIONSHIPS

Understanding the relationship between the AM process, the microstructure, and the resulting material properties is critical for optimizing AM techniques and material choices. The following factors are essential in determining the final microstructure:

THERMAL GRADIENTS AND COOLING RATES

The rapid heating and cooling cycles associated with AM processes result in steep thermal gradients that are different from traditional manufacturing processes. These gradients affect:

- **Solidification Rate**: High cooling rates result in fine microstructures, but they also increase the risk of defects such as porosity, residual stresses, and cracking.
- **Residual Stresses**: The thermal cycling associated with AM can lead to large temperature gradients, causing thermal stresses within the part. This is especially problematic for high-performance alloys like Inconel 718, where the residual stresses can significantly reduce the material's fatigue resistance [97].

POST-PROCESSING TECHNIQUES

- **Heat Treatment**: Post-processing heat treatments, such as stress relief annealing, can be used to alleviate residual stresses and modify the microstructure. For example, homogenization heat treatments on Inconel 718 after LPBF processing refine the microstructure, reducing the concentration of defects like microcracks and increasing mechanical properties.
- **Hot Isostatic Pressing (HIP)**: HIP is often used to reduce porosity and improve the density of AM parts. This post-processing method applies high pressure and temperature, which can lead to the formation of more uniform microstructures by eliminating internal voids.

ALLOY COMPOSITION

The addition of specific alloying elements plays a significant role in the solidification behavior and phase stability of AM parts.

- **Inconel 625**: The solidification and phase stability of Inconel 625 are influenced by elements such as niobium (Nb), which can alter the solidification path and the final phase distribution. The high thermal gradients during AM can lead to the formation of niobium-rich phases, affecting the overall mechanical performance [93].
- **Titanium Alloys**: The addition of alloying elements such as aluminum (Al) and vanadium (V) in Ti-6Al-4V affects the formation of the α/β phases, impacting the material's ductility, strength, and resistance to high-temperature creep.

INNOVATIVE TECHNIQUES AND THEIR IMPACT ON MICROSTRUCTURE

ULTRASOUND-ASSISTED ADDITIVE MANUFACTURING

In some advanced AM techniques, such as ultrasound-assisted AM, high-intensity sound waves are used during the printing process. This technique has been shown to refine the microstructure of materials like 316L stainless steel by promoting the formation of fine, equiaxed grains and reducing the anisotropy typically seen in conventionally printed parts. The ultrasound waves help to control the solidification process by introducing additional nucleation sites, which leads to a more uniform grain structure [94, 99].

FRICTION STIR PROCESSING (FSP)

Friction Stir Processing (FSP) is an effective post-processing technique for refining the microstructure of AM parts, particularly for alloys like aluminum and titanium. FSP involves a rotating tool that stirs the material, generating frictional heat and mechanical deformation that refines the microstructure. This technique has been used to improve the properties of aluminum alloys produced by wire-arc additive manufacturing (WAAM), resulting in improved grain structure, reduced porosity, and enhanced mechanical performance [99]. In the Figure 20, macro- and microstructure of XOZ section of the WAAM þ interlayer FSP component; (a) macrostructure; (b) microstructure; (c) magnified image of red dotted line area in (b); (d) magnified image of position d; (e) magnified image of position e defines the visual comparison.

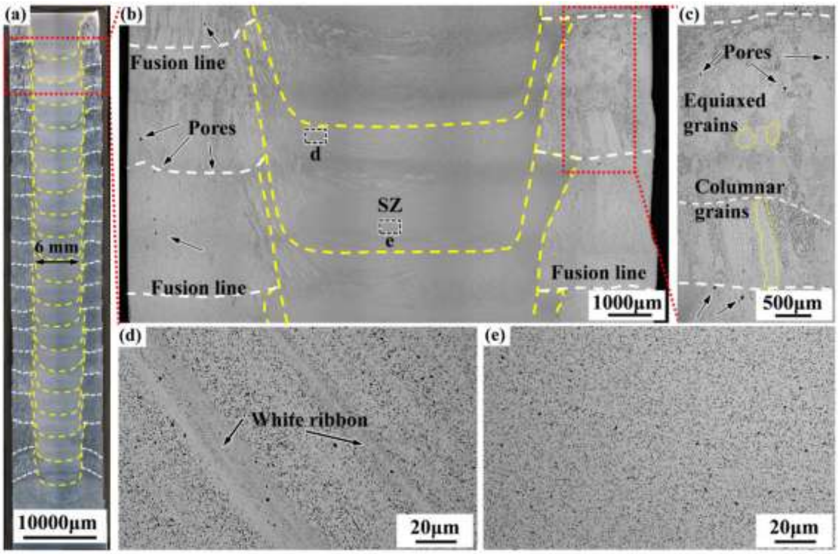


Figure 20 Macro- and microstructure of XOZ section of the WAAM þ interlayer FSP component [99]

GRAIN BOUNDARY ENGINEERING

Manipulating the characteristics of grain boundaries can significantly improve the mechanical properties of AM parts. For example, in superalloys like Inconel 718, modifying the grain boundaries at the atomic scale can reduce the tendency for hot cracking during solidification. This can be achieved through precise control of processing parameters or post-processing techniques like grain boundary engineering.

COMPARISON OF THE ADDITIVE MANUFACTURING METHODS MICROSTRUCTURAL EVALUATION

The microstructure evaluation of metal additive manufacturing techniques reveals significant differences that directly impact the mechanical properties and overall quality of the final product. While AM offers great design flexibility, each technique has its unique characteristics, and understanding the microstructural behavior is crucial to optimizing the final part's performance. Post-processing plays an essential role in improving properties such as strength, fatigue resistance, and dimensional stability, ensuring that AM-produced metal parts meet the requirements for advanced engineering applications.

Each metal AM method has unique microstructural characteristics that impact the mechanical properties, dimensional accuracy, and final application suitability of the parts produced. Techniques like SLM and DMLS produce parts with high strength but require post-processing to reduce residual stresses and improve surface finish. Methods like EBM and Binder Jetting offer lower porosity and residual stress, with EBM being suitable for tougher applications. Metal FDM and LMD can produce more customized parts but often require additional finishing to meet high-performance standards. Table 4 is depicted in the comparison of the method's microstructural evaluation of additive manufacturing.

Table 4 Microstructure evaluation of Metal Additive Manufacturing Methods

Characteristic	SLM (Selective Laser Melting)	EBM (Electron Beam Melting)	DMLS (Direct Metal Laser Sintering)	LMD (Laser Metal Deposition)	Binder Jetting	Metal FDM (Fused Deposition Modeling)
Energy Source	Laser	Electron Beam	Laser	Laser	Binder + Heat (Sintering)	Heat (Extrusion of Filament)
Cooling Rate	Rapid (high cooling gradient)	Slower cooling rate (vacuum environment)	Moderate	Variable (depends on material feed rate and power)	Low (slow process)	Slow (solidification occurs slowly)
Grain Structure	Fine, columnar grains along the build direction	Coarse, columnar grains	Fine microstructure, more uniform	Fine grains but directional variations	Coarser microstructure post-sintering	Highly anisotropic; direction-dependent
Porosity	Present (reduce with post-processing)	Low porosity	Low porosity	Low porosity (depends on deposition parameters)	Higher before sintering, reduced after	High porosity in the as-built state
Residual Stresses	High (due to rapid cooling)	Moderate (lower due to slower cooling)	Moderate to high	Moderate (depends on part geometry)	Low (no melting in initial stage)	High (due to uneven cooling)
Surface Finish	Rough (can be improved by post-processing)	Rough (improvement by heat treatment)	Smooth but can require post-processing	Variable, depends on nozzle and deposition speed	Rough before sintering	Rough (improvement by post-processing)
Mechanical Properties	High strength in the build direction; lower in lateral directions	High tensile strength, good toughness	Strong but direction-dependent	High strength (customizable based on deposition)	Lower mechanical properties post-sintering	Lower strength and toughness, highly anisotropic

Characteristic	SLM (Selective Laser Melting)	EBM (Electron Beam Melting)	DMLS (Direct Metal Laser Sintering)	LMD (Laser Metal Deposition)	Binder Jetting	Metal FDM (Fused Deposition Modeling)
Dimensional Stability	Potential warping due to residual stresses	Better dimensional stability	Dimensional accuracy is generally good	Varies, often requires post-processing for accuracy	High (requires sintering for final density)	Low accuracy, especially in the z-direction
Build Direction Effects	Anisotropic (properties depend on build orientation)	Anisotropic, but less than SLM	Anisotropic, but less than SLM	Can be controlled with parameter adjustments	Significant anisotropy (before sintering)	Significant anisotropy (depends on filament path)
Post-Processing	HIP, Heat Treatment, Surface Finishing	Heat Treatment (stress relief)	HIP, Heat Treatment	Heat Treatment, Surface Finishing	Sintering, HIP, Surface Finishing	Heat Treatment, Surface Finishing
Typical Applications	Aerospace, Medical Devices, Automotive	Aerospace, Biomedical Devices	Aerospace, Tooling, Automotive	Repair, Coating, Custom Parts	Prototype, Low Volume Production	Prototyping, Low-Cost Manufacturing

RELATED STANDARDS

Here are some key standards that relate to metallic AM processes and parts:

STANDARTS

ASTM F2924-14 – Standard Specification for Additive Manufacturing Titanium-6Al-4V (Ti-6Al-4V) ELI (Extra Low Interstitial) Alloy for Metal Powder Bed Fusion

- **Scope**: This standard provides specifications for the titanium alloy Ti-6Al-4V ELI used in metal powder bed fusion processes like Selective Laser Melting (SLM) and Electron Beam Melting (EBM).

- **Applications**: Aerospace, medical implants, and high-performance engineering parts.
- **Focus**: Material properties, powder characteristics, and process requirements.

ASTM F3049-14 – Standard Guide for Additive Manufacturing of Metal Parts

- **Scope**: This guide outlines best practices for additive manufacturing of metal parts, focusing on process controls, materials, and post-processing techniques.
- **Applications**: General-purpose guide for manufacturers involved in metal additive manufacturing.
- **Focus**: It covers areas like design for additive manufacturing (DfAM), material selection, and process parameters.

ISO/ASTM 52900:2015 – Additive Manufacturing — General Principles — Terminology

- **Scope**: This international standard defines the general terminology used in additive manufacturing, including terms specific to metal additive manufacturing.
- **Applications**: Used by anyone involved in the AM industry, from designers to manufacturers.
- **Focus**: Standardization of language and terms across industries and regions.

ISO 17296-2:2015 – Additive Manufacturing — General Principles — Part 2: Material Definitions

- **Scope**: Defines and categorizes materials for additive manufacturing, including metals. It specifies requirements for materials that can be used in AM processes, such as powder properties.
- **Applications**: This standard is crucial for developers of materials used in AM processes, especially for metallic powders.
- **Focus**: Material specifications, including chemical composition, particle size distribution, and flowability.

ISO 52915:2016 – Additive Manufacturing — Data Processing — File Format for the Exchange of 3D Models

- **Scope**: Specifies the data formats used to exchange 3D model data in additive manufacturing, including for metallic parts.
- **Applications**: Important for ensuring data consistency when transferring 3D model information between software and AM machines.
- **Focus**: Ensuring compatibility and quality in the transmission of files used in metal 3D printing.

ISO 17123 – Additive Manufacturing — Post-Processing of Metal Parts

- **Scope**: Covers the procedures for post-processing metallic parts produced through AM, such as heat treatment, surface finishing, and machining.

- **Applications**: Critical for ensuring that metal parts meet the required performance standards after the printing process.
- **Focus**: Standardizing post-processing steps to ensure the final part properties (e.g., mechanical properties, surface finish) meet application requirements.

ISO/ASTM 52921:2013 – Additive Manufacturing — Standard Terminology for Additive Manufacturing Technologies

- **Scope**: This standard provides a comprehensive vocabulary for additive manufacturing technologies, which includes specific references to metal AM processes.
- **Applications**: Important for ensuring clarity and consistency in the language used in AM specifications and contracts, especially in industrial applications.
- **Focus**: Standardizing terminology and definitions used in the context of additive manufacturing, including for metallic processes.

ASTM E2922-15 – Standard Guide for Characterization of Metal Powders Used for Additive Manufacturing

- **Scope**: Defines the requirements for characterizing metal powders used in AM processes, which directly influence the quality and properties of printed parts.
- **Applications**: Widely used by material suppliers and manufacturers to ensure the suitability of powders for specific AM processes.
- **Focus**: Characterization of powder materials, including particle size, flowability, chemical composition, and density.

ASTM F3184-16 – Standard Guide for Qualification and Validation of Additive Manufacturing Processes for Metal Parts

- **Scope**: This guide provides guidelines on how to qualify and validate metal additive manufacturing processes for specific applications, ensuring part performance.
- **Applications**: Aerospace, automotive, and other industries where precision and reliability are critical.
- **Focus**: Methods for qualifying and validating AM processes for metal parts to meet application-specific standards.

ASTM F2924-21 – Standard Specification for Additive Manufacturing of Metal Parts using Laser Powder Bed Fusion

- **Scope**: Focuses on laser powder bed fusion (LPBF) processes and provides material specifications for metal parts produced via this AM technique.
- **Applications**: Commonly used in aerospace, medical, and automotive applications.
- **Focus**: Specifies the characteristics of metal powders, print settings, and process controls necessary to achieve optimal results.

INDUSTRY-SPECIFIC STANDARDS

AEROSPACE (SAE, AS9100)

- **AS9100** is a widely recognized quality management standard for the aerospace industry. It provides the framework for quality assurance, including in additive manufacturing for aerospace parts. Aerospace companies often require certifications like **AS9102** for first article inspections (FAIs) for metal parts produced through additive manufacturing.

AUTOMOTIVE (IATF 16949)

- In the automotive industry, **IATF 16949** focuses on quality management in the production of parts, including those made using additive manufacturing. Compliance with this standard is essential for manufacturers looking to supply metal 3D printed parts to automotive OEMs.

MEDICAL (ISO 13485)

The **ISO 13485** standard is vital for the medical device industry, covering quality management systems for medical devices, including those produced via additive manufacturing processes. It includes stringent controls on materials, production, and post-processing steps to ensure safety and efficacy in medical implants

QUALITY CONTROL FOR METALLIC APPLICATIONS

Quality control (QC) in metallic additive manufacturing (AM) is a crucial aspect of ensuring the consistency, reliability, and performance of 3D printed metal parts, especially since AM processes introduce unique challenges compared to traditional manufacturing methods. As metal 3D printing is increasingly adopted in high-performance industries such as aerospace, automotive, medical devices, and more, effective quality control ensures that the parts meet all required specifications and performance standards.

Quality control in metallic additive manufacturing is a multifaceted process that includes ensuring the quality of raw materials (powders), monitoring in-process conditions, post-processing treatments, and conducting thorough mechanical and non-destructive testing. Given the unique nature of AM, where each part is built layer-by-layer, QC practices must be rigorously applied to ensure the parts meet required specifications, particularly for safety-critical applications in aerospace, automotive, and medical fields.

By maintaining strict quality control and using a combination of in-situ monitoring, NDT, mechanical testing, and traceability, manufacturers can ensure the high reliability and performance of metal 3D printed parts.

MATERIAL QUALITY CONTROL

- **Powder Quality**: Metal powders used in AM must meet stringent quality specifications to ensure consistent printing. QC involves checking:
    - **Particle Size Distribution**: Ensures uniformity in powder flow and melting behavior.
    - **Chemical Composition**: Verifies that the powder meets alloy specifications for the intended application.
    - **Moisture Content**: Excess moisture can affect powder behavior and part quality, leading to issues such as oxidation.
    - **Flowability and Bulk Density**: These properties are crucial for successful powder bed fusion processes like SLM or EBM.
- **Certification**: The metal powder supplier should provide certifications of material properties and specifications that comply with industry standards like ASTM or ISO.

PRE-PROCESSING AND DESIGN CONTROL

- **Design for Additive Manufacturing (DfAM)**: Ensuring that the design is optimized for the AM process can minimize defects and improve quality. This involves:
  - **Orientation and Support Structures**: The design should account for factors like overhangs, supports, and cooling rates during the printing process.
  - **Build Plan**: The build direction and layer strategy should minimize stress and distortions, especially in materials prone to warping.
  - **Software Simulation**: Using software tools to simulate the AM process can help predict potential defects and optimize build strategies before printing.

IN-PROCESS MONITORING AND CONTROL

- **Process Monitoring**: Real-time monitoring of various parameters during the additive manufacturing process helps to detect issues early. Some key parameters to monitor include:
  - **Laser Power and Spot Size**: In powder bed fusion processes (e.g., SLM or EBM), the power and size of the laser affect the quality and consistency of the melt pool.

    - **Temperature**: Temperature gradients during the build process can result in warping, cracking, or residual stresses.
    - **Powder Flow and Distribution**: Ensuring uniform powder distribution on the build platform can prevent defects caused by uneven melting or incomplete fusion.
    - **Build Rate and Layer Thickness**: These parameters affect the part's accuracy and mechanical properties.
- **In-Situ Monitoring Systems**: Some advanced AM systems include in-situ monitoring tools like:
    - **Optical and Thermal Cameras**: To monitor the melt pool and ensure consistent material deposition.
    - **Acoustic Sensors**: To detect anomalies such as a lack of fusion or excessive heat in the build.
    - **X-ray and CT Scanning**: To inspect internal features in real-time, particularly in complex geometries.

POST-PROCESSING AND HEAT TREATMENT

- **Heat Treatment**: Post-processing steps like annealing, stress-relieving, or aging are often required for metallic AM parts to achieve desired material properties (e.g., hardness, strength, and toughness).

    - **Consistency**: Temperature control and uniformity in post-processing are essential to prevent issues like distortion or cracking.
  - **Surface Finishing**: Surface quality is a critical factor in the performance of metal parts, particularly in medical or aerospace applications. Post-processing methods such as grinding, polishing, or shot peening are common.
  - **Dimensional Inspection**: After heat treatment, parts may experience dimensional changes due to residual stresses. QC often involves measuring the part dimensions to ensure they meet specifications.

Non-Destructive Testing (NDT): Non-destructive testing methods are widely used to verify the quality of metal parts without damaging them. Common NDT methods for metallic AM parts include:

  - **X-ray Computed Tomography (CT)**: A highly effective method for inspecting the internal structure of AM parts, including voids, cracks, and internal porosity.
  - **Ultrasonic Testing (UT)**: Used to detect internal defects such as voids or delaminations by sending high-frequency sound waves through the material.
  - **Laser Scanning and Structured Light**: These technologies can inspect the surface of parts for dimensional accuracy and detect any deviations from the CAD model.

- **Magnetic Particle Testing (MT)**: Can detect surface and near-surface defects in ferromagnetic materials, which are commonly used in AM.
- **Eddy Current Testing (ECT)**: Used to detect surface cracks and material conductivity variations in AM parts.

Various post-processing techniques used in additive manufacturing for both metallic and plastic parts, focusing on the enhancement of surface quality and mechanical properties [64].

MECHANICAL TESTING

- **Tensile Testing**: Measures the material's strength and elongation under tensile stress, which is important for determining the structural integrity of the part.
- **Hardness Testing**: Methods like Vickers or Rockwell hardness tests are commonly used to assess the hardness of AM metal parts, which correlates with wear resistance and overall part durability.
- **Fatigue Testing**: Fatigue resistance is critical in applications like aerospace or automotive. Parts may undergo cyclic loading to simulate in-service conditions and assess how they perform over time.
- **Impact Testing**: The Charpy V-notch test measures a material's toughness, especially important for safety-critical applications.

TRACEABILITY AND DOCUMENTATION:

- **Material Traceability**: It's crucial to maintain detailed records of the material batches used, including certification data, material certificates, and lot numbers.

- **Process Traceability**: QC involves recording all process parameters during the AM build, including machine settings, laser power, layer thickness, and any deviations from the planned build process.
- **Inspection Reports**: Detailed reports of testing, inspections, and certifications ensure compliance with industry standards (e.g., ISO 9001, AS9100) and that parts are fit for use.

CERTIFICATION AND COMPLIANCE:

- **Industry-Specific Certifications**: Depending on the application, parts may require certifications such as:
  - **AS9100 (Aerospace)**: Quality management system standard for the aerospace industry, which includes requirements for metal AM processes.
  - **ISO 13485 (Medical Devices)**: Requires strict quality control in manufacturing processes, including additive manufacturing for medical implants and devices.
  - **IATF 16949 (Automotive)**: Quality management standard for the automotive industry, which also applies to AM processes used in automotive parts.
  - **PED (Pressure Equipment Directive)**: Certification for parts used in high-pressure environments, which is relevant to some

metal AM applications like valves and pressure vessels.

FUNDAMENTAL TECHNIQUES AND TECHNOLOGIES: PART- II PLASTIC PARTS

An overview of additive manufacturing technologies applied to plastic materials, comprehensive review on plastic-based 3D printing processes, focusing on materials like PLA, ABS, and others, and exploring their various applications [59], the development of additive manufacturing (AM) for polymer composites, analyzing materials, printing technologies, and challenges [60], the progress in thermoplastic-based 3D printing technologies, challenges in materials selection, and the future trends of 3D printed thermoplastic components [61]. As a hybrid material application, hybrid AM systems that combine different materials such as metals and plastics, providing insights into process technologies, applications, and future directions for manufacturing integrated components [62],

There are many polymeric applications in the field. In this paper after mentioning all types of plastics and their applications in additive manufacturing, the aim is mainly exploring one of the ultra-high-performance polymer PEEK applications and its restraints.

There are different methods on the plastic based additive manufacturing. The most common ones are VAT Photopolymerization, Material Extrusion (MEX), Material Jetting and Binder Jetting methods and their sub classifications for plastic ones. Tabulated form of the additive manufacturing techniques depicted in

Table 5.

Table 5 Additive Manufacturing Techniques - Plastic Parts

Additive manufacturing technique	**Sub-classification**
VAT Photopolymerization	Continuous Liquid Interface Production (CLIP)
	Scan, Spin and Selective Photocure (3SP)
	Selective Light Activation (SLA)
	Digital Light Processing (DLP)
Material Extrusion (MEX)	Fused Deposition Modelling (FDM)
	Fused Filament Fabrication (FFF)
Material Jetting (MJ)	Multi Jet Fusion Process- Polyjet
	Multi Jet Modelling (MJM)
	Smooth Curvatures Photocurves (SCP)
Binder Jetting	High Speed Sintering (HSS)
	3D Printing (3DP)

Plastic materials mainly divided as thermoset and thermoplastic in application fields. Plastic applications of the additive manufacturing use vide variety of plastic materials and most common ones are Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Polycarbonates (PC), Poly Ether Ether Ketone (PEEK), Ether Ketone Ketone (PEKK), Polyetherimide (PEI; branded as Ultem), Nylon, High Impact Polystyrene (HIPS). The methods will be evaluated in the oncoming paragraphs but detailed material evaluation has been just limited for PEEK and PEEK application for polymer additive manufacturing.

A bunch of scientists called carbon 3D just introduced a totally new kind of 3D printing but they were actually inspired to make it from the science fiction series in 19th century. The conventional 3D printing involves a printing head that passes over and over across a platform depositing a thin layer of material in each time and this printing forms an object continuously out of a liquid resin in other words a bath of liquid resin that solidifies when light hits it. The platform dips into this resin and as it rises up you have a rejector underneath the resin pool that is projecting a series cross-sectional images that are in the exact shape of the object wanted to make. Platform slowly moves upwards the projector through different images the different cross-sections and it causes the object form in the shape wanted. Stereo lithography uses a laser to form the part from photo polymer resin as a platform moves down. Digital light processing uses photo polymers and uses a light source to solidify single layers at a time as a platform moves up. Carbon based 3D improved upon two methods with their Digital Light Synthesis (DLS) and Continuous Liquid Interface Production (CLIP) technology. Parts Produced with Selective Light Activation (SLA) and Digital Light Processing (DLP) have notoriously inconsistent mechanical properties because of the molecular structure that results from their single layer printing methods because DLS utilizes continuous production the resulting parts have better and more uniform structures therefore producing more consistent and predictable mechanical properties. Light from a light engine projects a sequence of Ultra-Violet (UV) images exposing a cross section of the part causing the UV curable resin to partially cure in precisely controlled path. Oxygen passes through the oxygen permeable window creating a thin layer liquid interface of uncured resin between the window and the printed part known as the dead zone. The dead zone is only a third of a human hair layer thick. In the dead zone oxygen prohibits light from curing the resin situated closest to the window thereby allowing the continuous flow of liquid beneath the part, just above the dead zone a UV light projected upwards causes a cascade like partial curing of the part. The sketch of the process is given below in Figure 21 CLIP Process Sketch. In this sketch numbered labels are given as follows; 1- Build Platform, 2- UV Curable Resign, 3- Dead Zone, 4- Oxygen Permeable Window and 5- Projector as mentioned in the previous section. This method is mainly used for rapid prototyping processes and fast manufacturing applications. In another area is the toy producing for children. Iconic objects are also produced with this additive manufacturing process. In all application area main objective is low costs, rapid production and high rate production. Geometry of the producing object could be very complex but it is not a problem for this producing method.

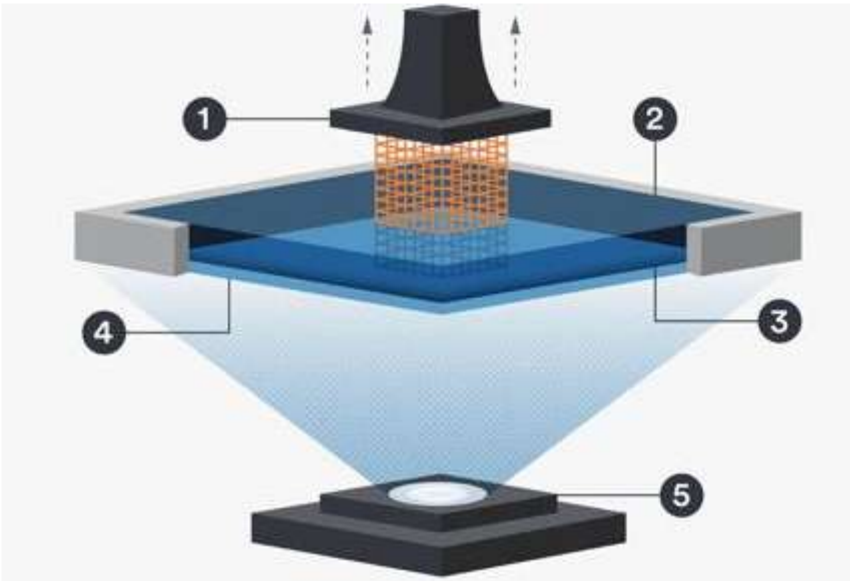
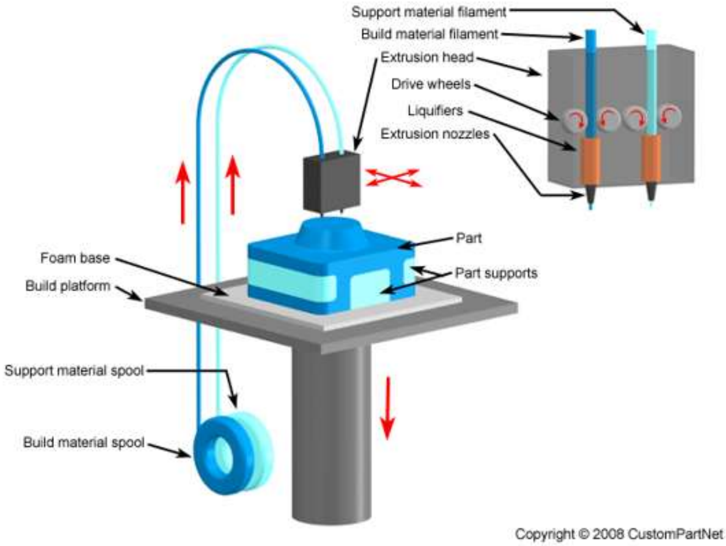


Figure 21 CLIP Process Sketch

In some cases, thermal curing operation is taken places. Printing alone is not produce the end part with its desired mechanical properties, a secondary carrying process bakes the parts in a thermal bath or oven which sets the mechanical properties by triggering another chemical reaction this then causes the material to strengthen achieving the desired final properties.

Scan, Spin and Selective Photocured (3SP) additive manufacturing is used with from hundred-micron layer thickness to the 50-micron layer thickness in applications. It offers superior surface finish and adoption areas of this technology have been in medical devices, injection molding and precision casting due to vector capability of self-calibration.

Fused deposition modeling (FDM) process, highlighting materials like ABS, PLA, and polycarbonate, and covers the applications and challenges in achieving high-quality results in polymer AM [67]. Fused Filament Fabrication (FFF) is a method for additive manufacturing which is used plastic based filament feedstock. In time this method is known as Fused Deposition Modeling (FDM) due to the unique manufacturer Stratasys and this companies belonging patents. After elapsed time and these patents obsolescence the method is changed to the FFF. This method is raised and mainly used for prototyping especially for automotive and aerospace outer geometry effects and bio-medical implant applications, today application area is wider. Method is used nozzle and extrusion principles, filaments goes inside the feeder, it reaches to entrance of the nozzle and heated up to the melting point then lamellar output layered on the substrate layer by layer [9]. The process schematic is shown in the Figure 22. Heating time diameters and dimensions of desired nozzle and die swell effect is important aspects for this process. Cooling rate of the lamellas on the surface dimensional accuracy are also important for the application.



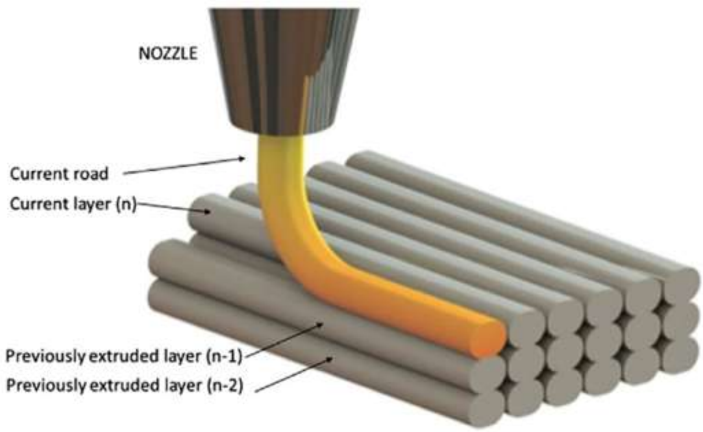


Figure 22 Fused Filament Fabrication [48], [9]

MATERIAL SELECTION FOR PLASTIC APPLICATIONS

The choice of material in plastic additive manufacturing depends largely on the desired properties of the final part, such as strength, flexibility, thermal resistance, and ease of printing. The article discusses the various polymer-based additive manufacturing technologies used in the automotive industry, such as SLA, SLS, and FDM, and the advantages of AM in terms of rapid prototyping and manufacturing complex geometries [69]. Each material has its advantages and limitations, and the decision will depend on the specific application and the printing method being used.

Plastic additive manufacturing (AM) involves using 3D printing technologies to create parts from various types of plastic materials. The most common types of plastic materials used in AM are selected based on their properties, such as strength, flexibility, heat resistance, and surface finish. Overview of the key materials are as follows:

Acrylonitrile Butadiene Styrene (ABS), ABS is tough, durable, and resistant to impact. It's commonly used in consumer products, automotive parts, and toys. It is often used in Fused Deposition Modeling (FDM) 3D printing. Good strength-to-weight ratio, moderate flexibility are advantages. Warping during printing; requires heated print bed is disadvantage.

Polylactic Acid (PLA), PLA is a biodegradable thermoplastic made from renewable resources like cornstarch or sugarcane. It is widely used in FDM/FFF 3D printing for prototyping and educational purposes. Easy to print with, no heated bed required, less warping, and environmentally friendly is main advantage unlike lower strength and heat resistance compared to ABS.

Polyethylene Terephthalate (PET/PETG), PET is known for its strength, durability, and chemical resistance. PETG (a glycol-modified version) is more flexible and easier to print. Used in both FDM and other AM processes. PETG is used for making mechanical parts, containers, and functional prototypes. **Advantages** are stronger than PLA and ABS, resistant to chemicals, low shrinkage.

Disadvantage is to be harder to print than PLA, may require a heated bed.

Nylon (Polyamide), Nylon is a strong, flexible, and abrasion-resistant material with excellent chemical resistance. Often used in FDM and SLS (Selective Laser Sintering) for functional parts, gears, and automotive components. **Advantages** are high strength, toughness, and wear resistance. **Disadvantages** are absorbing moisture from the air, which can affect print quality; requires high print temperatures.

Thermoplastic Polyurethane (TPU), TPU is a flexible, rubber-like material known for its elasticity, resilience, and abrasion resistance. Used for making flexible parts such as phone cases, seals, gaskets, and wearables. Highly flexible and durable. Difficult to print due to flexibility; requires specific print settings.

Polycarbonate (PC), Polycarbonate is a high-strength material known for its transparency and heat resistance. Used in applications requiring high impact resistance, such as automotive and aerospace parts. Excellent strength and toughness, good for high-temperature applications. Requires high print temperatures; prone to warping without a heated bed and proper printing environment.

High-Density Polyethylene (HDPE), HDPE is a versatile, lightweight, and chemical-resistant plastic often used in bottles and containers. Often used for making chemical containers, food-grade items, and other durable consumer goods. Good resistance to chemicals, moisture, and UV radiation. Tends to warp easily during the printing process.

Polypropylene (PP), Polypropylene is a flexible, low-density material that is resistant to fatigue, impact, and chemical corrosion. Widely used in packaging, automotive components, and medical devices. Chemical resistance, low friction. Difficult to print, requires special conditions like a heated bed and good adhesion.

Composite Materials (Carbon Fiber, Glass Fiber, etc.), These are reinforced plastics, where fibers like carbon or glass are embedded in a base plastic to enhance strength, stiffness, and thermal stability. Used in industrial and high-performance applications, such as automotive, aerospace, and robotics. Enhanced mechanical properties, lightweight. Requires specialized 3D printers with hardened nozzles due to abrasiveness of fibers.

Resins (for SLA and DLP), Liquid photopolymer resins are used in Stereolithography (SLA) and Digital Light Processing (DLP) 3D printing technologies. Used for high-precision parts, including dental, jewelry, and prototype models. High detail and smooth surface finishes. Brittle, may not be as durable as thermoplastics; post-processing required (washing, curing).

PVA (Polyvinyl Alcohol), PVA is a water-soluble material often used for support structures in 3D printing. Typically used with dual-extrusion 3D printers for creating complex geometries that require support. Soluble in water, making it ideal for dissolving away supports. Limited use for structural parts due to its low strength.

High-performance materials in aerospace and medical additive manufacturing must meet rigorous standards for strength, durability, and performance under extreme conditions. These materials often require specialized 3D printing technologies like metal additive manufacturing (for titanium, Inconel), high-temperature FDM (for PEEK and ULTEM), or SLA/DLP (for high-performance resins). Their applications span from aircraft parts to implants and surgical tools, where reliability and safety are critical.

High-performance materials used in additive manufacturing (AM) for aerospace and medical applications are specifically engineered to meet stringent requirements for strength, durability, biocompatibility, temperature resistance, and chemical stability. These materials are crucial for creating parts that must withstand extreme conditions, such as high temperatures, heavy mechanical stress, and exposure to various fluids or biological environments. Below are some of the key high-performance plastics used in these industries:

PEEK (Polyether Ether Ketone), PEEK is one of the highest-performing thermoplastics available for 3D printing. It offers excellent mechanical properties, including high strength, stiffness, and fatigue resistance, along with high thermal stability and chemical resistance. PEEK is used in aerospace for parts that must withstand high temperatures, such as engine components, connectors, and brackets. It is ideal for applications where lightweight yet strong materials are needed. PEEK is widely used in the medical industry for implants (such as spinal and orthopedic implants) because it is biocompatible, resistant to body fluids, and can be sterilized. It also has properties similar to bone, which helps in creating more natural-feeling prosthetics. High strength-to-weight ratio, excellent chemical resistance, high temperature resistance (up to 480°F/250°C), good wear resistance. Expensive, requires specialized high-temperature 3D printers, difficult to process.

ULTEM (Polyetherimide, PEI), ULTEM is a high-performance thermoplastic known for its excellent mechanical properties, including high tensile strength, stiffness, and dimensional stability at elevated temperatures. It also offers excellent flame retardancy. Aerospace Applications: ULTEM is used in aerospace for structural components that require high strength and heat resistance, such as brackets, ducts, and seals. It can withstand high temperatures and harsh environments without degrading. Medical Applications: ULTEM is also used for medical devices, especially in situations requiring sterilization and biocompatibility. It is used in surgical instruments, diagnostic equipment, and sterilization trays. High strength, high thermal stability (up to 340°F/170°C), biocompatible, flame-retardant, good electrical insulating properties. Expensive, challenging to process, requires high-temperature printers.

PAI (Polyamide-imide), PAI is an engineering thermoplastic known for its exceptional strength, heat resistance, and dimensional stability. It also has outstanding chemical resistance, making it suitable for harsh environments. Aerospace Applications: PAI is used for high-performance aerospace components, such as parts exposed to high temperatures and pressure, like seals and bearings. It is also used for fuel system components due to its chemical resistance. Medical Applications: PAI is used for medical devices that require high strength and thermal stability, such as surgical instruments, connectors, and implants. High temperature and chemical resistance, good mechanical properties at elevated temperatures, low wear, and friction. Expensive, difficult to process, requires specialized equipment.

PCTFE (Polychlorotrifluoroethylene), PCTFE is a high-performance plastic with excellent chemical resistance, low moisture absorption, and high dielectric properties. It also has good dimensional stability at a wide range of temperatures. Aerospace Applications: PCTFE is used in aerospace for components exposed to aggressive chemicals or extreme vacuum conditions, such as seals, gaskets, and valves. Medical Applications: It can be used in medical devices that require chemical resistance and a stable performance over time, such as fluid control systems and valve components. Excellent chemical resistance, low moisture absorption, good electrical properties. Can be difficult to process, high cost.

Poly Ether Ether Ketone (PEEK) has some demanding characteristics which are a semi crystalline structure, low density of comparing Titanium (Ti) or Stainless Steel (304 or 316), higher strength and tensile modulus, biocompatibility, similar characteristics of bone elasticity, easy processing capability without needs tooling , damage tolerances, high melting temperature (nearly 345 Celsius degree), high glass transition temperature, high temperature stability especially irradiation degradation resistance in high temperatures, ability to be solvent of composites and wide chemical additives, lower cost comparing the metallic counterparts (Ti, Pt, Au etc.) [1], [2], [6], [49]. These outrageous properties make it a controversial application area especially biomechanical, dental, orthopaedical, aerospace, automobile manufacturing. In one phase detail, it is used to manufacturing jet engine parts, air suction line parts, threaded parts, composites and structural parts of air vehicle apart from the biomedical applications. Figure 23 is depicted in the PEEK top performance and advance characteristics among the polymers.

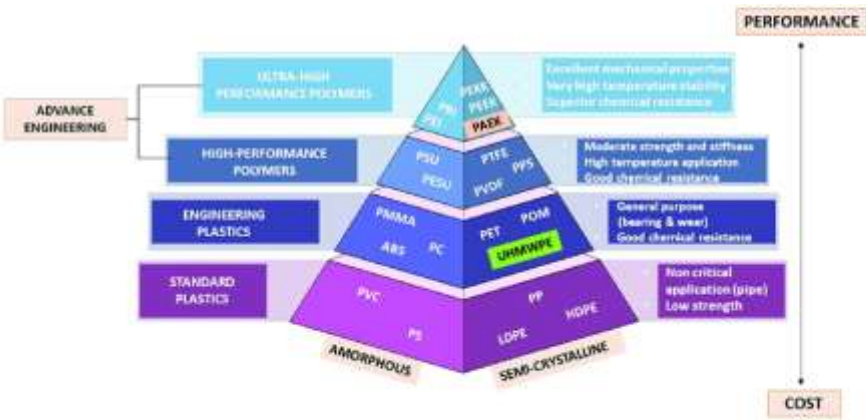


Figure 23 High Performance Polymers [49]

It is preferred in aviation and automobile industry mainly due to the thermoplastic behavior and recycle capability, processing parts apart from the autoclave and processing different manufacturing techniques such as, compression molding, injection molding, extrusion, circular molding and one up to date additive manufacturing method is Fused Filament Fabrication (FFF) which process is depicted in Figure 24 Fused Filament Fabrication parameters [50] known early as Fused Deposition Modelling (FDM) [4].

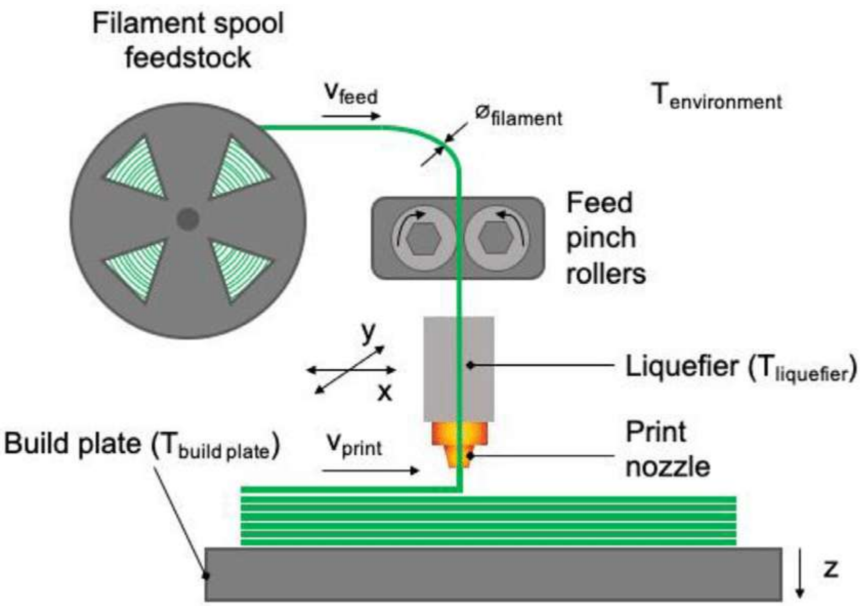


Figure 24 Fused Filament Fabrication parameters [50]

Nano particulate enhanced PEEK structure is currently one of the hot issues in the literature. Due to the fascinating properties of the material and widely application areas reinforced PEEK material is standing out in the front line of the scientific studies. Due to the hexagonal structure of pure PEEK material, nanometric scaled carbon fibers (CF), glass fibers (GF), graphite, hydrogen boron nitride (h-BN) are the selected additive materials for reinforcements. Pure PEEK has some disadvantages as matrix morphology and solubility due to organic polymers when physically combined with inorganic nanoparticles and this process could be resulted in agglomeration, weak homogenization and weaken the structure [6]. These nanometric particles are changed the mechanical, tribological and rheological characteristics of the pure PEEK. CF and GF are reinforced and positive effect on the strength characteristics but h-BN particle reinforced samples are observed that adhesive and thermal conductivity enhancements achieved. For covalent connection on nitrogen and boron h-BN particles is preferred besides its hexagonal structure, van der Valls connections between the layers creates weakness in between the layers and it causes easily shared. Hence h-BN reinforcements provide excellent solid lubricating, good thermal conductivity, strong chemical inertness. It is the reason preferred to use high temperature purposes areas in aviation and automobile industry [6]. More proceeding progress is risen with adding multiple nanometric additives in the sample. Results are observed that, in multi additive reinforced samples the best strength to elongation ratio and abrasive behavior and thermal conductivity characteristic concluded with 20 % CF and 4-8 % h-BN. Increasing the h-BN content is not resulted in the abrasive or thermal conductivity characteristics [6].

In filament fabrication, literature indicates that pure PEEK powder is acquired from the company of Victrex 450 G/PF, Germany, with a diameter of 1.75 $\pm$ 0.05 mm, this powder is validated with nanoscale additives of CF and/or h-BN with a single or double screw extruders, (FILABOT, VT, USA), with an optimized screw speed 30 rpm and processing temperature of 340 Celsius degree in order to get a fabricated filament. For the 3D printer APIUM P155 GmbH Fused Filament Fabrication printer is widely used with ASTM D638 Type V standard equivalent. In this machine, nozzle diameter is indicated 0.4 mm and nozzle temperature specified as in between 400-450 Celsius degree [9]. The test samples and micro voids in a part observed with fabrication process and end process with compression molding operation.

Reinforced high-performance materials in additive manufacturing (AM) combine base high-performance polymers with reinforcing fibers or particles (e.g., carbon fiber, glass fiber, Kevlar, or aramid) to improve their mechanical properties, such as strength, stiffness, and wear resistance. These reinforced materials are specifically designed for industries that require not only durability but also the ability to withstand extreme stresses, temperatures, and mechanical loads, such as aerospace, automotive, and medical applications.

REINFORCED HIGH-PERFORMANCE MATERIALS

The review focuses on the advancements in 3D printing of polymeric nanocomposites, the impact of various nanofillers, and how this influences the mechanical and thermal properties of the printed parts [68]. Most commonly used **reinforced high-performance materials** for additive manufacturing in aerospace and medical sectors are as follows:

CARBON FIBER REINFORCED PEEK (CF-PEEK)

- **Base Material**: PEEK (Polyether Ether Ketone)
- **Reinforcement**: Carbon fibers
- **Properties**: Carbon fiber reinforcement significantly enhances the mechanical properties of PEEK, improving its tensile strength, stiffness, and resistance to wear and thermal degradation.
- **Aerospace Applications**: CF-PEEK is used for high-strength aerospace components like engine parts, brackets, connectors, and internal structures that need to withstand high temperatures and mechanical stress.

- **Medical Applications**: In the medical field, CF-PEEK is used in implants (especially for spinal and orthopedic applications) due to its mechanical strength, biocompatibility, and lightweight nature.
- **Advantages**: Superior strength-to-weight ratio, high stiffness, excellent thermal resistance (up to 480°F/250°C), wear resistance, and dimensional stability.
- **Disadvantages**: Expensive, requires specialized 3D printers capable of handling high-temperature materials.

CARBON FIBER REINFORCED ULTEM (CF-ULTEM OR PEI-CF)

- **Base Material**: ULTEM (Polyetherimide)
- **Reinforcement**: Carbon fibers
- **Properties**: The carbon fiber reinforcement improves the mechanical strength, stiffness, and dimensional stability of ULTEM, making it ideal for applications in high-performance and high-stress environments.
- **Aerospace Applications**: CF-ULTEM is used for structural parts in aerospace, including interior components, brackets, ducts, and heat shields. Its combination of high strength, thermal resistance, and low weight makes it suitable for aircraft components.
- **Medical Applications**: CF-ULTEM is also used for medical devices that require high strength and durability, including surgical tools, diagnostic devices, and sterilization trays.
- **Advantages**: High temperature resistance (up to 340°F/170°C), excellent strength and rigidity, flame-retardant, biocompatible.
- **Disadvantages**: More challenging to print compared to non-reinforced ULTEM, expensive.

CARBON FIBER REINFORCED NYLON (PA-CF)

- **Base Material**: Nylon (Polyamide)
- **Reinforcement**: Carbon fibers
- **Properties**: Carbon fiber reinforcement boosts the strength, stiffness, and heat resistance of nylon while reducing the material's inherent flexibility. This creates a high-performance material that retains the durability of nylon but with enhanced structural properties.
- **Aerospace Applications**: Used for lightweight, high-strength components like brackets, gears, and enclosures in the aerospace industry. The carbon fiber provides increased stiffness and dimensional stability, reducing warping during printing.
- **Medical Applications**: In medical applications, carbon fiber reinforced nylon is often used for creating durable, lightweight structural components like surgical instruments or parts for medical devices requiring higher mechanical performance.
- **Advantages**: Lightweight, strong, increased stiffness, improved heat resistance, excellent for functional parts.
- **Disadvantages**: Carbon fiber filaments can be abrasive, so they require hardened nozzles for 3D printing. Can also be challenging to print without proper settings.

GLASS FIBER REINFORCED PEEK (GF-PEEK)

- **Base Material**: PEEK (Polyether Ether Ketone)
- **Reinforcement**: Glass fibers
- **Properties**: Glass fiber reinforcement enhances the stiffness, tensile strength, and dimensional stability of PEEK while keeping it lightweight. Glass fibers are less expensive than

carbon fibers, providing a cost-effective option without sacrificing too much in terms of mechanical performance.

- **Aerospace Applications**: Used in aerospace for components that need high strength and resistance to high temperatures, such as internal structural components and brackets. The material is particularly useful for parts that need to handle mechanical loads and harsh conditions.
- **Medical Applications**: GF-PEEK is used in medical implants where high strength, wear resistance, and biocompatibility are required, such as in spinal or joint replacements.
- **Advantages**: High strength, excellent wear resistance, good heat resistance (up to 480°F/250°C), good chemical resistance.
- **Disadvantages**: Requires specialized 3D printing systems that can handle high-temperature materials. Less lightweight than carbon fiber-reinforced PEEK.

CARBON FIBER REINFORCED POLYAMIDE (PA-CF)

- **Base Material**: Polyamide (Nylon)
- **Reinforcement**: Carbon fibers
- **Properties**: Carbon fiber reinforcement gives nylon materials a significant boost in terms of stiffness and strength, while still maintaining the material's relatively low weight and ease of use in printing.
- **Aerospace Applications**: This material is ideal for creating parts such as mounting brackets, structural components, and lightweight supports in the aerospace industry.
- **Medical Applications**: Due to its rigidity and toughness, carbon fiber reinforced polyamide is used for lightweight,

strong structural components like surgical instruments and various functional medical devices.

- **Advantages**: High stiffness, excellent mechanical properties, lightweight, high impact strength, good fatigue resistance.
- **Disadvantages**: The material can be challenging to print with if not done properly (especially with regard to temperature and print speed). Abrasive nature of carbon fiber requires hardened extruders.

KEVLAR REINFORCED NYLON (KEVLAR-PA)

- **Base Material**: Nylon (Polyamide)
- **Reinforcement**: Kevlar fibers
- **Properties**: Kevlar, known for its use in bulletproof vests, significantly improves the toughness and impact resistance of nylon. When combined with nylon, it creates a material that is extremely tough and resistant to wear, tear, and impact forces.
- **Aerospace Applications**: Kevlar-reinforced nylon is used in aerospace for parts that need to resist impact and mechanical stress, such as functional prototypes, end-use components, and lightweight yet durable parts.
- **Medical Applications**: Kevlar-reinforced nylon can be used in medical tools and devices where superior impact resistance and toughness are required, such as surgical instruments and protective gear.
- **Advantages**: Extremely high tensile strength, impact resistance, lightweight, excellent for wear-resistant applications.

- **Disadvantages**: Difficult to print with, as Kevlar can be abrasive on nozzles. Printing at high temperatures can be tricky.

GLASS FIBER REINFORCED NYLON (PA-GF)

- **Base Material**: Nylon (Polyamide)
- **Reinforcement**: Glass fibers
- **Properties**: Glass fibers add extra strength, stiffness, and dimensional stability to nylon, improving its performance under mechanical stress and high-temperature conditions. This makes it suitable for a wide range of industrial applications.
- **Aerospace Applications**: Glass fiber-reinforced nylon is used for structural components such as gears, brackets, and functional prototypes that require excellent mechanical properties and impact resistance.
- **Medical Applications**: It is used for manufacturing parts like surgical instruments, prosthetic parts, and medical device housings that need higher strength and durability.
- **Advantages**: Improved stiffness and strength, better dimensional stability, good chemical resistance.
- **Disadvantages**: More abrasive than regular nylon, requiring hardened nozzles for 3D printing.

REINFORCED THERMOPLASTIC ELASTOMERS (TPE)

- **Base Material**: TPE (Thermoplastic Elastomer)
- **Reinforcement**: Various reinforcements (e.g., glass fibers or carbon fibers)

- **Properties**: Reinforced TPE combines the flexibility and elasticity of rubber with increased mechanical properties, making it ideal for use in flexible yet strong parts.
- **Aerospace Applications**: TPE is used in aerospace for seals, gaskets, and vibration-damping components that need to be flexible but still strong enough to handle mechanical loads.
- **Medical Applications**: Reinforced TPE is used for wearable medical devices and flexible components in medical devices that require both durability and elasticity.
- **Advantages**: Excellent flexibility, impact resistance, abrasion resistance, and low weight.
- **Disadvantages**: Less common in high-performance aerospace applications compared to other reinforced thermoplastics, but still useful in specific cases.

Reinforced high-performance materials are crucial for applications in aerospace and medical fields where mechanical strength, durability, and resistance to high temperatures and harsh conditions are paramount. Carbon fiber and glass fiber reinforcements are particularly popular, but each material has its advantages depending on the specific needs of the application. These materials enable manufacturers to create lighter, stronger, and more reliable parts for highly demanding industries.

NONUNIFORMITY AND POST PROCESS

There are important process parameters effecting the part quality for FFF method. Nozzle diameter, heating section length of the material feeder before the extrusion process in the nozzle, feed stock rate, nozzle and environment temperatures, filament properties especially if the filament is reinforced with nanometric or micro particles or fibers homogeneity is one of the crucial importance for the filament. Figure 24 shows that the main parameters for the fused deposition process excluding the nozzle characteristics, extrusion parameters and die swell aspect. “Die Swell” factor has to be studied for better part quality. Die Swell is a scientific concept, it is mainly resulted from the surface tensions of the molded material and especially in all scales extrusion application but if the working area is a micro space, it is more important to produce proper part layers in FFF [5], [50].

In 3D printing with Fused Filament Fabrication (FFF) technique, the micro cracks and voids in the sample and melting pool dimensional changes along the lamella are the problematic issues in additive manufacturing applications in both metallic and polymeric applications. In order to abstain this problematic phenomena’s, optimization of printing parameters is required. Diameter of the nozzle is one of the parameters and decreasing the nozzle diameters resulted in the decreasing the gaps between the lamella and it has a positive impact but decreasing the nozzle diameter is affected the thermal instability on the melting pool and it is resulted in inhomogeneous diameter in the layer of the samples additionally power consumption and residual thermal stresses are greater. Another one is “die swell” ratio, materials extruded in the tip of the nozzle is circular shaped and increased diameter besides to be a same diameter of the nozzle tip. In order to prevent the process from this kind of unexpected diameter change, die swell ratio has to minimized. It is minimized with increasing the length of extrusion process starting point to the nozzle tip. The exaggerated resemble of the nozzle effect is given Figure 25.

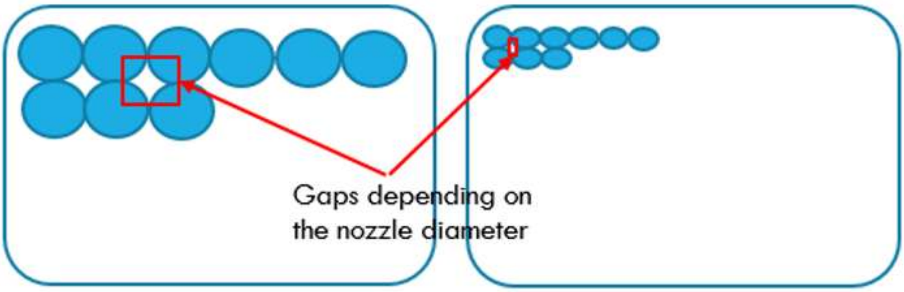


Figure 25 Nozzle Gap Effect

NONUNIFORMITY IN ADDITIVE MANUFACTURING

Nonuniformity refers to the variations in material properties, surface quality, and geometric accuracy within a 3D-printed part. These variations can be caused by several factors related to the nature of the additive manufacturing process, and they can impact the final performance of the part. Here's an overview of the main types of nonuniformity in AM:

MATERIAL NONUNIFORMITY

- **Layer-Based Process**: Most additive manufacturing processes (like Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS)) build parts layer by layer. This means the properties of each layer might differ from one another due to variations in the deposition or curing process.
  - **Internal Structure Variations**: Layers may have inconsistent bonding between them, creating weak interfaces. This can result in **anisotropy**, where the part has different properties along different axes (e.g., stronger in the XY-plane but weaker in the Z-plane).
  - **Infill Density**: Variations in infill density can cause parts to be stronger in some areas and weaker in

others, affecting the part's overall mechanical properties.

- **Material Flow Variations**: In processes like FDM, the extrusion of material can be inconsistent due to temperature fluctuations, nozzle size, or material feed problems. These inconsistencies can result in **surface roughness** or weak spots.
- **Porosity**: AM processes like SLS and SLA might result in porous structures, especially if the material is not fully sintered or cured, leading to nonuniform internal densities that affect strength, durability, and other properties.

GEOMETRIC NONUNIFORMITY

- **Resolution and Accuracy**: Different AM technologies have varying levels of resolution and accuracy. For example, FDM might have noticeable layer lines and a lower resolution than SLA or powder-bed-based methods like SLS.
- **Overhangs and Warping**: Certain geometries, especially those with large overhangs or intricate details, may not print uniformly due to insufficient support structures or thermal expansion. This can lead to **warping** or **curling** of edges.
- **Support Structures**: Parts that require support during printing may exhibit nonuniformity in the areas where the supports were removed. The removal of these supports can leave behind marks, rough surfaces, or slight deformations.
- **Thermal Effects**: In processes like SLS or metal AM, thermal gradients during the building process can cause uneven expansion or contraction of the material, leading to **distortion**, cracks, or residual stress.

SURFACE QUALITY NONUNIFORMITY

- **Layer Lines**: In methods like FDM, the surface can appear rough due to visible layer lines. The quality of the surface is often dependent on print resolution and layer height.
- **Texturing**: Parts printed with low resolution may have a rough texture. If the resolution is too low, the part might not meet aesthetic or functional requirements.
- **Residual Stress and Warping**: Differential cooling rates between layers can induce residual stresses, which may cause parts to warp or deform after printing, especially in polymers or metals.

POST-PROCESSING IN ADDITIVE MANUFACTURING

Post-processing refers to the secondary operations performed on a 3D-printed part after it has been printed to improve its properties, finish, or performance. These processes can address nonuniformity issues, improve mechanical properties, and prepare parts for their intended use. There are several types of post-processing techniques, and the appropriate one often depends on the AM technology used and the desired outcome.

POST-PROCESSING METHODS

1. **Support Removal**
    - In 3D printing methods like FDM, SLA, or SLS, support structures are often used to support overhanging parts during printing. After the print is finished, these supports need to be removed, which can affect the surface finish.
    - **Methods**: Support removal can be done manually (by breaking away or cutting) or using a chemical bath (such as in the case of soluble supports).

- **Challenges**: Support removal can leave behind marks, rough spots, or deformations, requiring additional cleaning or sanding.

2. **Sanding and Polishing**
   - **Purpose**: To improve surface finish, remove layer lines, and smooth out rough areas.
   - **Methods**: Sanding, abrasive blasting, or polishing can be done using fine-grit sandpaper or specialized tools.
   - **Challenges**: Sanding can affect the geometry of the part if not done carefully, and it may not remove deeper imperfections.
3. **Chemical Smoothing (for FDM and SLA)**
   - **Purpose**: To reduce surface roughness and achieve a smoother finish by dissolving excess material at the surface.
   - **Methods**:
     - **SLA**: Post-curing the part in a chemical vapor can smooth the surface and increase its mechanical properties.
     - **FDM**: Chemical smoothing with solvents (such as acetone for ABS) can help smooth the surface and remove visible layer lines.
   - **Challenges**: Not all materials respond well to chemical smoothing, and overexposure can damage the part.
4. **Annealing**
   - **Purpose**: To relieve internal stresses and improve mechanical properties, such as strength and heat resistance.

- **Methods**: The part is heated to a specific temperature and then cooled slowly to reduce the internal stress caused by the 3D printing process. This is especially relevant for **FDM** and **SLS** prints.
- **Challenges**: Annealing requires precise temperature control, as overheating or improper cooling can distort the part or affect its properties.

5. **Post-Curing (for SLA and DLP)**
   - **Purpose**: To fully cure the part, increasing its mechanical strength and stability. SLA and DLP prints are typically cured under UV light after printing.
   - **Methods**: Exposing the part to UV light or placing it in a UV oven for several hours ensures that all the resin is fully cured.
   - **Challenges**: Inadequate curing can result in soft or weak parts, while over-curing can lead to brittleness.
6. **Heat Treatment**
   - **Purpose**: To improve mechanical properties by improving the polymer's crystallinity or reinforcing the material.
   - **Methods**: This may involve heating the part to a specific temperature to increase strength or flexibility, or cooling it quickly to lock in a particular microstructure.
   - **Challenges**: Similar to annealing, heat treatment must be controlled carefully to avoid dimensional changes or warping.
7. **Surface Coatings**

- **Purpose**: To enhance the surface properties of the part, such as wear resistance, aesthetic finish, or water resistance.
- **Methods**: Coatings like **paint**, **powder coating**, or **electroplating** are applied to the surface.
- **Challenges**: Surface coatings can add additional weight or alter the mechanical properties of the part, so it's important to ensure compatibility with the material used.

8. **Infiltration**
   - **Purpose**: To fill pores and improve strength or surface finish.
   - **Methods**: Infiltrating a part with a liquid or resin (common in **SLS** or **polyjet** printing) can improve its structural integrity or surface smoothness.
   - **Challenges**: The infiltration process can result in changes to part dimensions or finish if not carefully controlled.
9. **Laser Sintering or Welding (for Metal AM)**
   - **Purpose**: To improve the surface finish and material density of parts created by metal additive manufacturing processes.
   - **Methods**: Laser sintering or direct energy deposition techniques can be used to reflow or melt areas of the part, improving density and mechanical properties.
   - **Challenges**: Requires high precision to avoid damaging the part, especially in complex geometries.

Nonuniformity in additive manufacturing is an inherent challenge due to the layer-by-layer nature of the process, material behavior, and thermal effects. However, the post-processing methods available can significantly mitigate these issues, improving the mechanical properties, surface quality, and overall performance of the printed parts. By carefully selecting and applying post-processing techniques, manufacturers can achieve high-quality, functional parts that meet the needs of their applications.

Avoiding **nonuniformity** in additive manufacturing (AM) involves addressing the inherent challenges in the 3D printing process that can lead to variations in material properties, geometry, and surface finish. While some level of nonuniformity is often unavoidable due to the nature of additive manufacturing, there are several strategies, both during the design and printing phases, that can help reduce or eliminate these issues. Below are key strategies to avoid nonuniformity in additive manufacturing:

COMPARISON OF THE METHODS

Fused Deposition Modeling (FDM) / Fused Filament Fabrication (FFF), FDM (or FFF) is one of the most commonly used 3D printing methods. It involves extruding a thermoplastic filament through a heated nozzle, which deposits the material layer by layer to build up the final part. It's the most common 3D printing technology for desktop-level machines. Cost-effective, widely available, and relatively easy to use, supports a wide range of thermoplastic materials, such as PLA, ABS, PETG, and Nylon, Great for prototyping and low- to medium-volume production, fast and efficient for creating parts with simple geometries are main advantages. Limited to lower-resolution and somewhat rough surface finishes compared to other methods. Material strength and thermal properties may not be as high as other methods like SLA or SLS. Requires support structures for overhangs, which can impact post-processing. Prototypes, functional parts, tooling, jigs, fixtures, and low-volume production runs are main applications.

Stereolithography (SLA), SLA uses a laser or projector to cure liquid resin, layer by layer, in a vat of photopolymer resin, known for producing high-resolution prints with smooth surface finishes. Extremely high accuracy and resolution, producing smooth surfaces, can create very detailed and intricate parts, some resins can have properties similar to traditional plastics, such as flexibility, toughness, and heat resistance are advantages. Limitations are relatively slower than FDM due to the layer-by-layer curing process, requires post-processing like cleaning (with isopropyl alcohol) and curing (with UV light), resin materials can be more expensive than standard thermoplastic filaments. Highly detailed prototypes, models, dental applications, jewelry, and high-resolution parts for the aerospace and medical industries are applications.

Selective Laser Sintering (SLS) – Plastic Variant, SLS uses a laser to selectively sinter (melt and fuse) small particles of plastic powder, layer by layer, to form solid parts. It doesn’t require support structures because the un-sintered powder around the part provides support during the build. Producing complex geometries with high strength and durability, no need for support structures, as the surrounding powder supports the part during the build, printing parts with a variety of thermoplastic materials like Nylon, TPU, and polystyrene are main advantages. Limitations are requiring a powder handling system and post-processing (e.g., powder removal and sintering), machines and materials are more expensive compared to FDM or SLA, lower resolution compared to SLA, though better than FDM. Functional prototypes, low- to medium-volume production parts, aerospace components, automotive parts, and end-use functional parts are application areas.

Multi Jet Fusion (MJF), similar to SLS in that it uses a powder bed process, but instead of using a laser, it uses an inkjet array to apply fusing agents onto a powder bed, which is then heated to fuse the powder into solid layers, the process builds parts with high speed, good material properties, and high resolution. Faster than SLS and SLA, with better surface finishes and resolution than traditional SLS, produces strong parts with excellent mechanical properties, no support structures required, as the un-sintered powder supports the part, suitable for full-color parts when using specific materials are advantages. Limitations are expensive equipment and materials, requiring post-processing (e.g., powder removal) before parts are ready for use, limited material options compared to FDM or SLA, though expanding. Functional prototypes, complex end-use parts, aerospace, automotive, consumer goods, and medical applications are application areas.

PolyJet / MultiJet Modeling (MJM), PolyJet 3D printing uses inkjet technology to jet photopolymer resins onto a build surface in ultra-thin layers, which are then cured with UV light, multiple materials can be used in the same print job, including flexible, rigid, or transparent resins. Advantages are extremely high resolution and fine detail, comparable to SLA, allows multi-material and multi-color printing in a single build, smooth surfaces and high accuracy, ideal for creating realistic prototypes, can print flexible, rigid, and transparent parts. Expensive machines and consumables, the materials used (photopolymers) can be more brittle than other thermoplastics requires post-processing to remove support structures are limitations. Highly detailed prototypes, medical devices, consumer goods, jewelry, and parts requiring different material properties are application areas.

Continuous Liquid Interface Production (CLIP), CLIP uses a photochemical process to rapidly solidify photopolymer resin, with a continuous flow of material, allowing for much faster printing than traditional SLA or DLP (Digital Light Processing), developed by Carbon3D, CLIP produces parts using a continuous UV light source to cure resin. Advantages are faster than SLA due to the continuous nature of the printing process, high resolution and smooth surface finishes, parts can be functional and durable with advanced resins. Requiring proprietary equipment and materials (typically supplied by Carbon3D), limited material choices compared to other 3D printing methods are limitations. Functional prototypes, medical devices, automotive parts, and consumer products are applications.

Direct Ink Writing (DIW), DIW uses a nozzle to extrude a paste-like material (such as a polymer or composite) and deposits it layer by layer. This is often used for materials that can be extruded in a semi-solid state, DIW can be used with a variety of materials, including thermoplastics, composites, and even food-grade materials. Advantages are ability to print with a wide range of materials, including soft, flexible, or composite materials, used for functional applications with specialized materials. Limitations are not as widely used or as fast as other methods, material extrusion may be less precise than other methods, leading to lower resolution. Specialized applications like biomedical printing, food printing, and flexible or composite material printing.

Table 6 depicts in the comparison of the plastic additive manufacturing methods including post-process needs and application areas.

Table 6 Comparison of Plastic Additive Manufacturing Methods

Method	Materials	Precision	Speed	Post-Processing	Applications
FDM / FFF	PLA, ABS, PETG, Nylon, TPU, others	Medium	Fast	Moderate (support removal)	Prototypes, functional parts, jigs, fixtures
SLA	Photopolymer resins	Very high	Slow	Extensive (cleaning, curing)	High-detail prototypes, medical, jewelry
SLS	Nylon, TPU, PS, PA, others	Medium	Moderate	Post-sintering	Functional prototypes, end-use parts, tooling
MJF	Nylon, TPU, others	High	Fast	Post-processing (powder removal)	End-use parts, functional prototypes
PolyJet / MJM	Photopolymer resins	Very high	Moderate	Moderate (support removal)	Multi-material parts, detailed prototypes
CLIP	Photopolymer resins	Very high	Very fast	Minimal	Functional prototypes, automotive, medical devices
DIW	Polymers, composites, food, others	Low	Moderate	Moderate	Specialized applications (biomedical, food etc.)

- **FDM** is the most cost-effective and widely available method, ideal for prototyping and low-volume production but with lower resolution.
- **SLA** and **PolyJet** are great for high-resolution, detailed prototypes, with SLA offering more material options and PolyJet excelling in multi-material printing.
- **SLS** and **MJF** are strong choices for functional prototypes and end-use parts, especially for parts requiring high strength and durability.
- **CLIP** offers the speed of SLA with higher resolution, making it ideal for rapid production of functional parts.
- **DIW** is highly specialized, suited for custom applications in medical or food printing.

To be conclude, each method has distinct advantages depending on the specific needs of the application such as part complexity, material requirements, resolution, and cost efficiency.

RHEOLOGICAL FUNDAMENTALS IN ADDITIVE MANUFACTURING

There is in-depth scientific overview of the rheological considerations in polymeric materials for additive manufacturing (AM), focusing on their impact on printability, structural integrity, and post-processing properties. This discussion encompasses various AM techniques, including Fused Deposition Modeling (FDM), Direct Ink Writing (DIW), and Stereolithography (SLA), and highlights recent advancements in rheological modeling and material design.

VISCOSITY AND SHEAR BEHAVIOR

Polymeric inks for AM typically exhibit shear-thinning (pseudoplastic) behavior, where viscosity decreases with increasing shear rate. This property is crucial for smooth extrusion through nozzles and the maintenance of filament shape post-deposition. For instance, inks with low viscosity at high shear rates facilitate extrusion, while higher viscosity at low shear rates ensures the deposited filament retains its shape without sagging or spreading. The Herschel–Bulkley model is often employed to characterize such non-Newtonian fluids, incorporating yield stress and flow behavior index parameters [119,120]

In small scale, viscosity is a behavior for fluidic substances, think of the layers as a stack of cards and each layer having a slightly different velocity than the neighboring layers. The same happens when shearing a liquid, as illustrated below, where you conceive many "fluid layers" sliding between a fixed lower plate and a moving upper plate. The shear rate is then the difference in velocity between two fluid layers, divided by the layers' distance. Fluid layers are introduced to aid, helping in the description as no "thick" fluid layers exist in the real world, as real velocity fields vary smoothly. The shear rate is also described below to the right, by the first mathematical relation. The basic schematic is given in Figure 26 Fluid shear stress and shear force. Viscosity is defined basically as shear stress divided by the shear rate.

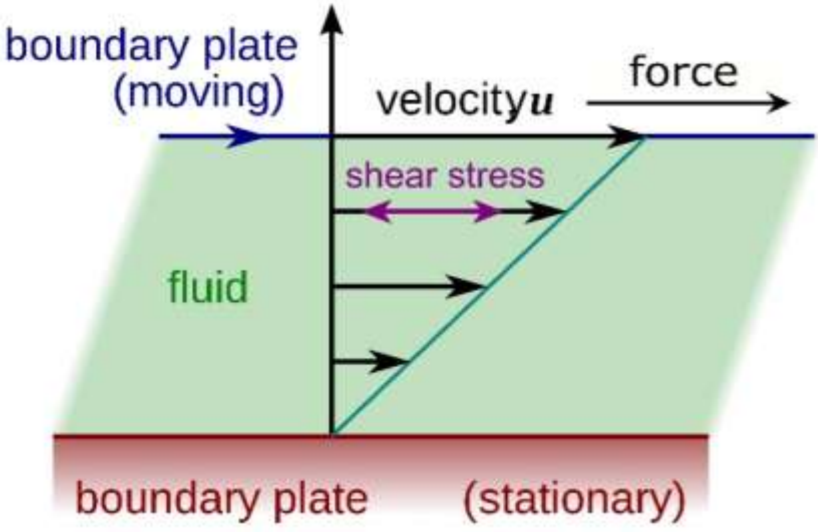


Figure 26 Fluid shear stress and shear force [121]

The basic formulations as following,

$$\text{Shear rate} = \dot{\gamma} = \frac{\text{velocity difference}}{\text{distance}} = \frac{dv}{dy}$$

$$\text{Shear stress} = \sigma = \frac{F}{A} = \frac{\text{Force}}{\text{Area}}$$

$$\text{Viscosity} = \eta = \frac{\sigma}{\dot{\gamma}} = \frac{\text{Shear stress}}{\text{Shear rate}}$$

Viscosity is critical characteristic feature of the fluids and specific instruments are used to define the viscosity known as rheometers.

Viscosity (steady-shear viscosity, melt viscosity, apparent viscosity) is to define how “thick” or resistant to flow a material is under shear and especially for polymers in FDM / MEX (Material Extrusion), melt viscosity at high temperature is critical is it is too high leads to poor extrusion; on the other hand, if it is too low resulted in sagging or loss of shape after deposition [133].

In other words, viscosity o highlights the knowledge gap between the function of rheology in various processing operations and the importance of rheology in the development, characterization, and assessment of the morphologies of polymeric materials, and offers ideas for enhancing the processabilities of polymeric materials in advanced processing operations. Rheology plays a crucial role in the morphological evolution of polymer blends and composites, influencing the type of morphology in the case of blends and the quality of dispersion in the cases of both blends and composites Figure 27 depicts the behavior within basic sketch.

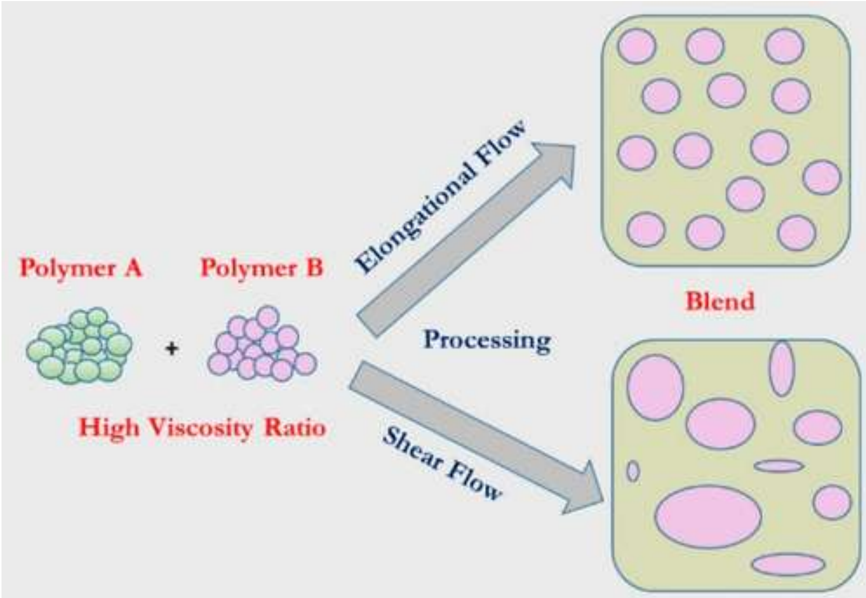


Figure 27 Rheological effects on morphology [133]

It is mainly known that non-Newtonian behavior is shear thinning (viscosity decreases as shear rate increases).

All polymers could be shared with three regions which is shown on the Figure 28, shear rate independent at low shear rates (deformation isn't large enough to disentangle polymer chains) is a straight line called zero shear region. Then viscosity becomes shear rate dependent and it normally decreases as called as shear thinning region and materials have less resistance to flow and flow is more easily and that is because of the molecular changes start to shear against each other and once they completely aligned no entanglement anymore then we reach the infinite shear region that again shear rate independent because this is no entanglement anymore the chains are stretched to the maximum extent. Typical viscosity flow curve, normally only meshed up to this point because the very high shear rate in your process to ever to close to it for spinning, fiber blowing etc. But material extrusion is focused on the shear thinning region.

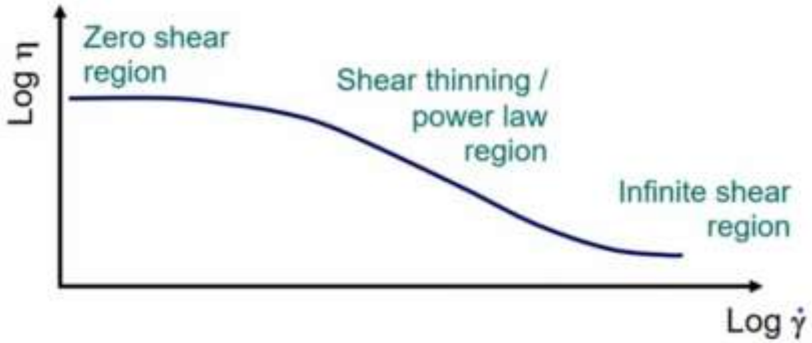


Figure 28 Viscosity flow curves

Shear thinning / shear thickening is a feature of fluidic behavior, shear thinning is very common in extrudable inks, melts, pastes. It helps material flow through nozzle/nozzle entry under high shear, but then regain structure once deposited [134]. Shear thickening may show up in suspensions or highly filled pastes, making flow more difficult at high shear rates; often undesirable in most AM processes unless specifically needed [134].

In the material extrusion process in particularly 3D printing which is shown on Figure 29, building platform includes extrusion head or in other words print head feeding by at least one thermoplastic material inside and in heals or melts then out of the nozzle extruded material layered to the build part.

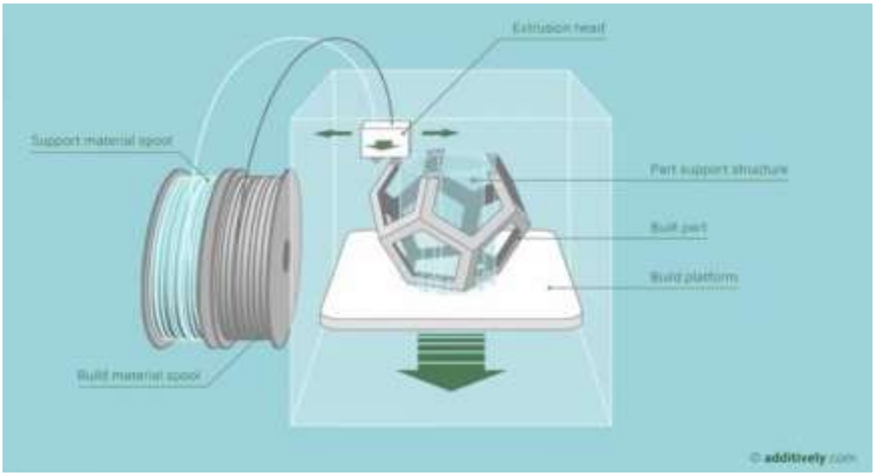


Figure 29 3D Printing schematic

ELASTIC AND VISCOUS MODULUS

When certain amount of shear force is applied a substance, material starts to deform. Elastic modulus is a kind of quantity that predicting elastic material deformation with a defined stress. It is a kind of analogy that how fast the material flows happening. Viscoelastic behavior is dependent on the material chemicals, process temperature, pressure and other related physical constraints.

The balance between the elastic (storage) modulus (G′) and the viscous (loss) modulus (G″) determines the material's ability to support its structure during and after deposition. A higher G′ relative to G″ indicates a more solid-like behavior, which is beneficial for maintaining the shape of printed features. Conversely, a higher G″ suggests a more fluid-like behavior, which can enhance layer adhesion and fusion [124,125].

Characterizing how much elastic “solid-like” behavior versus viscous “liquid-like” behavior is present. High G′ helps with shape stability; G″ relates to energy dissipation under deformation [134].

Also, the relaxation times (how fast a material relaxes stress after deformation) are important in FDM/filament melts and in inks. If the relaxation time is too long, stresses built during extrusion may not relax, and causing defects.

There are four main model given in the literature as following; **Power-law / Ostwald-de Waele model** where ($n<1$) gives shear thinning, ($n>1$) gives shear thickening. The consistency index (k) and flow index (n) are fitted from flow curves [134], **Herschel–Bulkley model** which adds a yield stress, useful for pastes/concrete etc.[136], **Viscoelastic models** Maxwell, Kelvin-Voigt, Generalized Maxwell etc., to describe storage/loss moduli, relaxation spectrum [138] and **Temperature-dependence models** Arrhenius behavior or WLF (Williams-Landel-Ferry) type equations for polymer melts. Used to relate viscosity to temperature.

YIELD STRESS AND PRINTABILITY

Yield stress is the minimum stress required to initiate flow. Materials with appropriate yield stress values are essential for controlling extrusion and ensuring the stability of printed structures. Incorporating fillers or adjusting polymer concentrations can modulate yield stress to achieve desired printability and structural fidelity [126].

The stress required to initiate flow, the value of the stress below yield stress, material behaves more like a solid; above it, it flows. Important for shape retention after deposition, avoiding slumping [136].

Printability deepens on several different physical properties as thixotropy / time-dependent behavior, temperature dependence, fillers / particle content / solid loading, apparent shear rate in nozzle / extrusion conditions. Thixotropy / Time-Dependent Behavior is mainly about the material and material’s viscosity or structure changes over time under shear or rest (e.g. structure breakdown under shear and recovery when at rest). Very relevant for inks that need to flow through nozzle but then set up (recover structure) quickly to retain shape [134]. Temperature Dependence is especially for thermoplastics and polymer melts (e.g. for FDM), viscosity depends strongly on temperature; higher temperature reduces viscosity and may increase flow, but may also reduce shape stability or cause degradation. Fillers / Particle Content / Solid Loading is that high filler loading (e.g. ceramic particles in a polymer matrix) significantly raises viscosity, enhances yield stress, alters shear thinning/thickening behavior. Must be optimized to be printable [137]. Apparent Shear Rate in Nozzle / Extrusion Conditions is related that shear rates in nozzles during extrusion are high; the measured "steady shear" or "apparent" shear rates in the rheological tests need to cover the relevant range. Also wall slip, melt fracture, pressure drop: these may arise under high shear [138].

There are many factors for printability for additive manufacturing in particular material extrusion type of productions such as FDM. These factors are shown and summarized by the Figure 30. Feedstock delivery is the one of the main factors, having a board staff machine with a filament conveying to nozzle with a wave form which is not a constant cross section creates quality problems. Heaters and thermocouple locations is another factor for temperature control. Temperature is one of the crucial impact factors for both viscosity and rheological behavior of the material. Feedstock quality stabilization of the filament diameter and mechanical, rheological, thermal and optical properties desired to not change in production with different cross-sectional area during process. Processing process parameters is another important factor with part orientation effected on the temperature field and in particular, smaller sections, thin-thick parts, thin-walled parts warpage effects have to be considered for accurate building part. As a final product, stair stepped like structure, density irregularities could be observed and the finishing processes are required. Finishing processes with polishing to a certain tumbling or vapor smoothing are common depending on the material type. And that all effects of the process and properties of the components that.

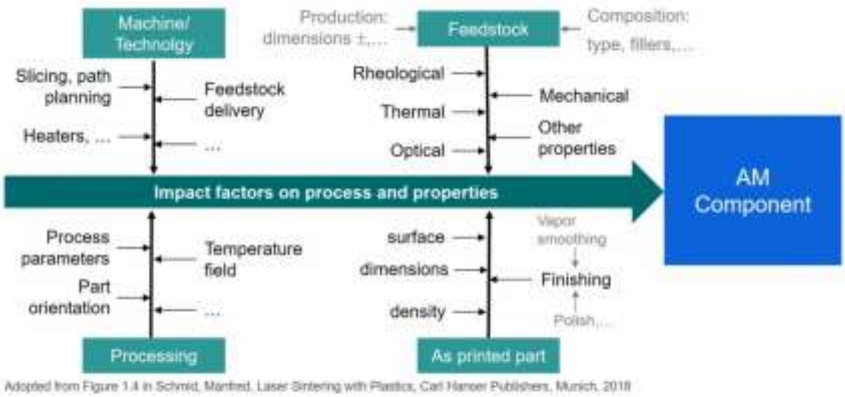


Figure 30 General impact factors on the properties of AM components

RHEOLOGICAL CONSIDERATIONS ACROSS ADDITIVE MANUFACTURING TECHNIQUES

FUSED DEPOSITION MODELING (FDM)

In FDM, the extrudate's shape stability is influenced by the material's rheological properties. Materials exhibiting yield stress in low shear conditions can prevent dripping and maintain filament shape during deposition. Additionally, the die swell phenomenon, where the extrudate diameter increases upon exiting the nozzle, is affected by the material's elasticity and relaxation time. Materials with lower elasticity tend to exhibit minimal die swell, leading to improved surface resolution of printed parts [127].

In polymer-based filaments (different PLAs) studied across temperatures 130 210 °C: zero-shear viscosities ~10^4 Pa·s for some commercial PLA filaments at ~170 °C, filament made in lab ~10^3 Pa·s. Relaxation times also varied (e.g. ~0.243 s, ~0.295 s, ~0.03 s) [127].

Critical parameters along the filament pass or path staring to feeding of the filament, the filament goes through the feeding gears and needs enough flexural modulus for to spool the filament on the material and then it's going in hear as a column strength as shown in the Figure 31 because the filament is used as a piston to push and pump to the nozzle and it has an effect on buckle, buckling is not wanted in process. The temperature dependent modulus and meshed the dynamic mechanical analysis are required in process. The filament fed into the nozzle, and it melts in the nozzle. The melting really depends on the heat flux and the thermal conductivity of the polymer filament as well as the filament diameter and the feed rate. The heat conduction is going to wall to the center, the thick of the material (diameter) is important (the large filament is 2.85) we need more time to melt, comparing to 1.75 mm. Pushing really fast, it is not allowed the material enough time to be melted. Then the blue section in the sketch goes down and some stops happening for melting catch up. These parameters are shown on the Figure 31.

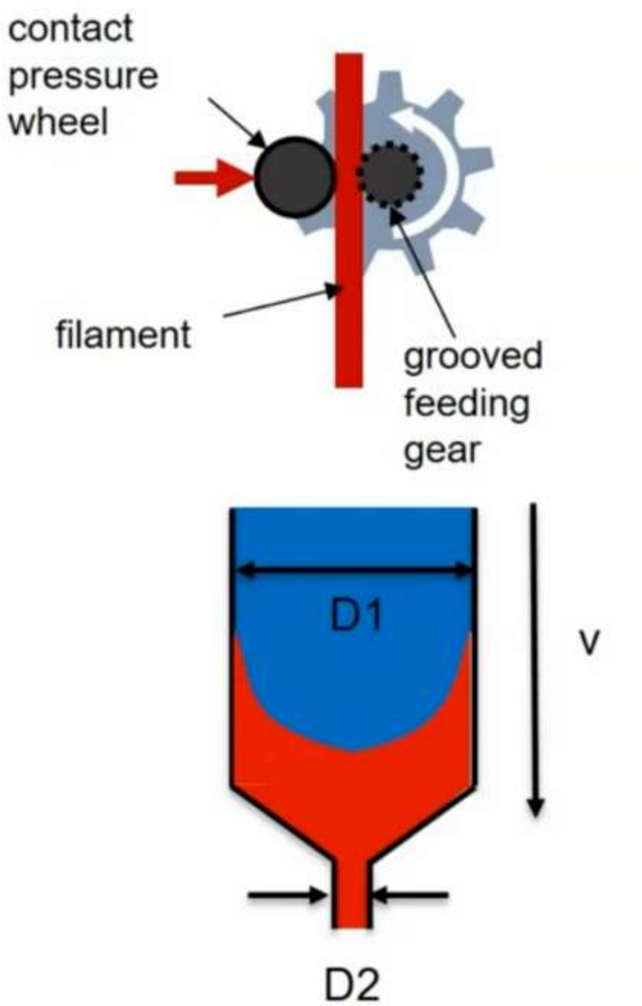


Figure 31 Critical parameters on the filament path

In order to understand this behavior Differential Scanning Calorimetry (DSC) and Laser Flash Analysis (LFA) is needed. In the end of the nozzle some volatiles are come out, because these material extrusion printers are so much used in home environment have more problems comparing industrial ones. How to get rid of volatiles during printing and the methods are defined as TG-FTIR or TG-GCMS.

The next step is material coming out of the nozzle showing in the picture, in order to material to flow melts needs sufficiently low viscosity to be pushed through the nozzle to forced comes from the solid filament pushing like a piston and it should be strong enough to push the melt flow. And it is also important a well-defined diameter, to change the diameter out in progress and capillary diameter rheometer to mesh the viscosity because we squeezing something out of a thin nozzle we want to know about the shear rate dependence viscosity.

DIRECT INK WRITING (DIW)

DIW relies on inks with shear-thinning and thixotropic properties to facilitate smooth extrusion and shape retention. For example, silica aerogel inks require optimal rheology to ensure printability and structural integrity. The incorporation of nanoparticles can enhance the rheological behavior, providing the necessary support for complex geometries and overhangs during printing [125].

STEREOLITHOGRAPHY (SLA)

In SLA, the resin's viscosity must be low enough to allow for recoating and high enough to prevent excessive spreading during curing. Typically, a viscosity under 5 Pa·s at 30 s^{-1} is desired to ensure smooth layer formation and adequate curing [128].

Recent studies have employed advanced rheological models to predict and optimize the printability of polymeric inks. For instance, the Giesekus model, incorporating parameters like the relaxation time and elasticity, has been used to simulate flow dynamics within FDM nozzles. This approach allows for the identification of elastic instabilities and the optimization of nozzle designs to enhance printing efficiency and reliability [129,130].

The incorporation of fillers, such as talc, calcium carbonate, silica, and nanoclays, into polymer matrices can significantly alter the rheological properties, affecting both printability and the mechanical performance of the final printed parts. For example, the addition of 30 wt% talc or calcium carbonate and 3 wt% nanoclay to polypropylene copolymers has been shown to improve the rheological behavior, leading to better processability and enhanced mechanical properties of the printed components [131].

A comprehensive understanding of the rheological properties of polymeric materials is essential for optimizing additive manufacturing processes. By tailoring viscosity, elasticity, yield stress, and incorporating appropriate fillers, it is possible to enhance printability, structural integrity, and functionality of 3D printed parts. Advanced rheological modeling further aids in predicting and refining these properties, paving the way for more efficient and reliable additive manufacturing techniques.

APPLICATIONS LEVERAGING RHEOLOGICAL OPTIMIZATION

BIOMEDICAL DEVICES AND TISSUE ENGINEERING

Hydrogels with tunable rheology for DIW to create scaffolds mimicking extracellular matrices.

Shear-thinning and yield stress crucial for cell viability during extrusion and shape fidelity post-printing.

In hydroxypropyl cellulose-based filaments, complex viscosity dropped about one order of magnitude when temperature increased from 150→200 °C. The shear-thinning slope (exponent) ranged between ~ –0.28 to –0.74 [139].

FUNCTIONAL COMPOSITES AND ELECTRONICS

Polymer nanocomposites with conductive fillers requiring precise rheological control to ensure printability and electrical percolation networks.

Rheology affects filler dispersion and alignment during printing, impacting conductivity and mechanical strength.

In a study of PLA-Alumina composite filaments for FDM, mixtures with alumina ~50-70 vol% were prepared, rheology measured in 200–240 °C. Fillers raised viscosity and affected printability [137].

LIGHTWEIGHT STRUCTURAL COMPONENTS

Additive manufacturing of filled polypropylene or polyamide composites for automotive or aerospace uses.

Rheology-tailored to balance extrusion ease and final part mechanical properties.

SMART AND RESPONSIVE MATERIALS

Polymers with stimuli-responsive fillers (e.g., shape-memory polymers) that require fine-tuned rheological properties for multi-material AM techniques.

Implications for process and print quality depends on several parameters as given following, shape fidelity / sagging / collapse is depending on the related to yield stress and storage modulus on the other words, if yield stress is too low or G′ too small, deposited layers may deform under their own weight. Interlayer adhesion requires enough melt mobility, if viscosity too high or relaxation times too long, the material may not fuse well between layers. Clogging, melt fracture is explained as at too high shear or too viscous melt, extruder might stall, or flow may become unstable. Resolution and surface finish is related with the extrudate swell, die swelling, melt elasticity and shear thinning affect how accurately the shape tracks the nozzle path [140].

Table 7 is comparative table of rheological parameters for several additive manufacturing (AM) processes / materials (DIW, FDM, vat photopolymerization etc.), drawing from recent studies. These numbers give a sense of the ranges of viscosity, yield stress, storage modulus etc. for printable materials. (Units in SI unless otherwise noted.) [141].

Table 7 Comparison of rheological behavior of AM techniques

AM Process / Material	Viscosity / η	Yield Stress (τ_γ)	Storage Modulus G′ (at rest / low strain)	Shear-Thinning / Flow Index n or related exponent	Other Notes / Thresholds / Criteria
DIW – Hydrogel / Soft Inks	~10^2 – 10^6 mPa·s at ~0.1 s^{-1} shear rate	~10 – 10^3 Pa, sufficient for shape fidelity	G′ ~100 – 10^4 Pa (must have G′ > G″ for structural integrity)	n ≈ 0.3 – 0.6 (pronounced shear thinning)	Recovery time / self-healing < ~10 s to retain shape post-deposition
DIW – High-Loading Polymer / Ceramic Inks (PDMS + metal/ceramic fillers)	(Not always viscosity explicitly listed) but formulations with high filler show very high G′ values, indicating very stiff/solid-like resting behavior	From ~200 Pa up to ~11,000 Pa depending on filler loading and composition	G′ from ~4 × 10^4 Pa to ~2.8 × 10^6 Pa in high filler inks	n not always given explicitly, but flow behavior is strongly shear-thinning in extrudable inks	Note: extremely high yield stress or G′ can make printing impossible, regardless of applied pressure, if the ink can't flow through nozzle.
DIW – Ceramic / Porcelain Pastes	~10^2 Pa·s scale viscosities for porcelain clay pastes in DIW at	Yield stresses in the range 10^2 – 10^3 Pa (oscillatory stress /	G′ ~10^5 – 10^6 Pa for paste at rest / low deformation	Exhibits shear-thinning: viscosity drops with increasing shear rate;	Dimensional accuracy depends on balancing dispersant content etc., to keep

AM Process / Material	Viscosity / η	Yield Stress (τ_γ)	Storage Modulus G′ (at rest / low strain)	Shear-Thinning / Flow Index n or related exponent	Other Notes / Thresholds / Criteria
	low/moderate shear rates	threshold stresses)		Newtonian plateau sometimes observed at higher shear rates (~20-85 s^{-1})	viscosity high enough for shape retention but not so high that nozzle pressure becomes unmanageable.
DIW – TCP Ceramic Inks	Viscosity decreases with increasing shear rate; from high at low shear to lower at higher shear (shear-thinning)	$\tau_\gamma > 0$; specific values depend on formulation. In some samples G′ (rest) ~10 MPa, which implies quite large yield stress at rest before flow begins.	G′ initial (static) ~10 MPa for some PVA/TCP mixtures; loss modulus G″ smaller under small stress/low shear	n < 1 (shear-thinning) in Herschel-Bulkley fits	For printable behavior, G″ overtakes G′ under sufficient shear, enabling flow; when shear stress increases, system transitions from elastic or semi-solid behavior to flow.
FDM – PLA-based Filaments	Viscosity at shear rates typical of nozzle (≈1000 s^{-1}) varies among PLA variants; some have lower viscosity enabling easier flow, others higher for shape-	Yield stress / effective similar threshold behavior observed in complex viscosity curves, and under extrusion; exact numeric yield stress often less	Rest-state or lower strain moduli not always reported; often more focus on viscosity vs shear rate and extrudability, die swell, etc.	Flow index / non-Newtonian / shear-thinning behavior strongly influences performance; better printability correlated with more pronounced	Other factors: die swell, melt elasticity, filament feeding; shape stability in stand-off region (between nozzle tip and previous layer) is influenced by melt viscosity

AM Process / Material	Viscosity / η	Yield Stress (τ_y)	Storage Modulus G′ (at rest / low strain)	Shear-Thinning / Flow Index n or related exponent	Other Notes / Thresholds / Criteria
	holding and less sagging.	emphasized but shape stability and non-Newtonian behavior critical.		shear thinning.	+ cooling behavior.
Vat Photopolymerization (SLA / DLP / MSLA) – Dental Resins etc.	Viscosity ~0.1 – 1.5 Pa·s (i.e. 100-1500 mPa·s) at moderate shear rates (~10-50 s^{-1}) and ambient temperature (~25-30 °C) for DLP/MSLA; SLA sometimes up to ~3 Pa·s under less strict recoating constraints.	Yield stress often low; enough to prevent sagging but low enough to allow recoating; often yield stress combined with zero shear viscosity / rest viscosity to set window. Specific numeric yield stress less often published.	Storage modulus at rest must be enough to avoid dripping / sagging; G′ > G″ in non-cured resin under low disturbance; but exact values vary by formulation.	Shear-thinning index modest; many resins are close to Newtonian at low shear, with mild shear thinning helps in recoating or wiping.	Critical printability window: too high viscosity → slow recoating / poor leveling; too low → sagging, loss of resolution. Trade-offs with layer height, exposure, peel forces.

To summarize the Table 7 and put together these data it can be extracted some rough “design windows” for extrusion and DIW of soft/hydrogel inks, viscosity in rest / low shear: ~10^2 to 10^6 mPa·s; yield stress ~10 1000 Pa; G′ ~10^2 10^4 Pa. For ceramic pastes (more solid-like), G′ can be very large (10^5 10^6 Pa), viscosity rest very high (≈10^2 Pa·s or more), but flow at higher shear needs to be feasible. For PLA-based FDM melts, viscosity at nozzle shear rates (≈10^3 s^{-1})

must be moderate (< some threshold) to extrude; strong shear-thinning behavior helps. Yield stress is less often directly quoted, but implicit in shape retention etc. For vat resins, viscosity ≤ ~1 3 Pa·s is typical under operating conditions; mild shear thinning and fast recovery, low yield stress so they flow when recoated.

EXPERIMENTAL SETUPS FOR RHEOLOGICAL CHARACTERIZATION

ROTATIONAL RHEOMETER

Rotational rheometer is a device which confining the liquid between a cone and a plate. Hypothetical fluid layers are a basis of the controlled volume and applied shear stress is resulted in the shear rate. The shear stress directly coming from the applied torque. Cone angle could be changing depending on the testing perquisites. This kind of rheometer is widely used the applications with a restriction of there is no evaporation happens. Figure 32 shows the basics of the rotational rheometers.

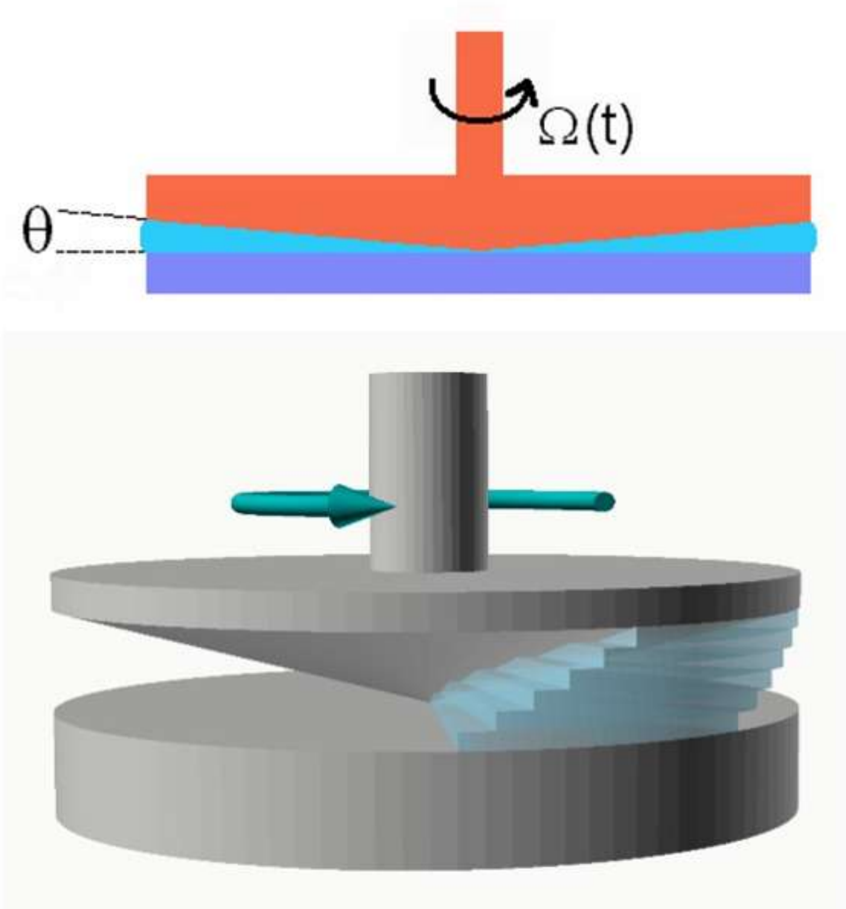


Figure 32 Basics of Rotational Rheometer [121]

Viscoelastic behavior is an important characteristic for the fluids such a shear rate dependence of the viscosity is a significant rheological property. All substance has rheological properties and to obtain the rheological information of the substance tests have been done with specific rheometers. A rotational rheometer with cone-and-plate or parallel plate geometry is commonly used. Specifically getting the information about the shear stress vs. shear rate to determine viscosity and shear-thinning behavior. Then flow curves could be drawing, these curves give information about the flow characteristics of the substance. Oscillatory tests mainly set to measure storage modulus (G′) and loss modulus (G″) over a range of frequencies to evaluate viscoelasticity. Yield Stress is determined via stress ramp or creep tests where flow initiates. Using time-dependent shear protocols like hysteresis loops (up-down shear rate sweeps) or step-shear experiments is known as “Thixotropy”. Figure 33 depicts that the measuring part turns in one direction in rotational rheometer, on the other hand turning both sides or oscillates around the axis in the oscillatory test.

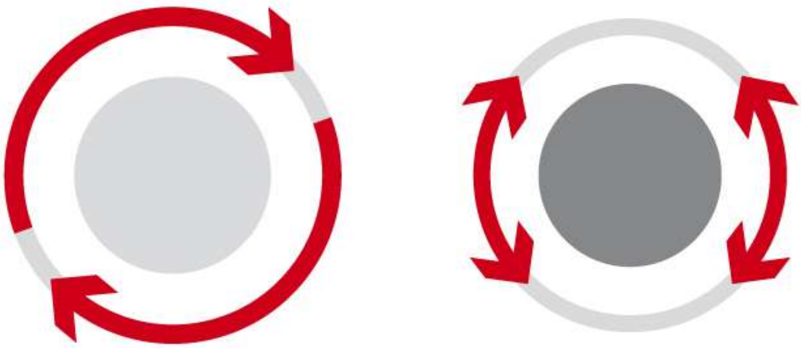


Figure 33 Rotational and oscillation movements [122,123]

As an example of a performance polymeric application printing temperature is defined as 180–230°C for PLA, and rheometer equipped with a temperature stage to simulate printing temperatures for temperature control. Protocol starts with pre-shear sample at a high shear rate (~100 s^{-1}) to erase thermal history, then perform shear rate sweep from 0.01 to 1000 s^{-1} to capture viscosity profile. Conduct oscillatory frequency sweep at low strain (within linear viscoelastic region) to get G′ and G″. And then conduct stress ramp test to detect yield stress. Figure 34 shows a generic example of the rheometer and sub- sections. In this figure there are two different version defined stress and strain-controlled ones and main difference is input force generation and gathering information from digital or analogue. The measuring head of a rheometer contains the drive motor and encoder which measure and set the previously mentioned torque, deflection angle, and speed.

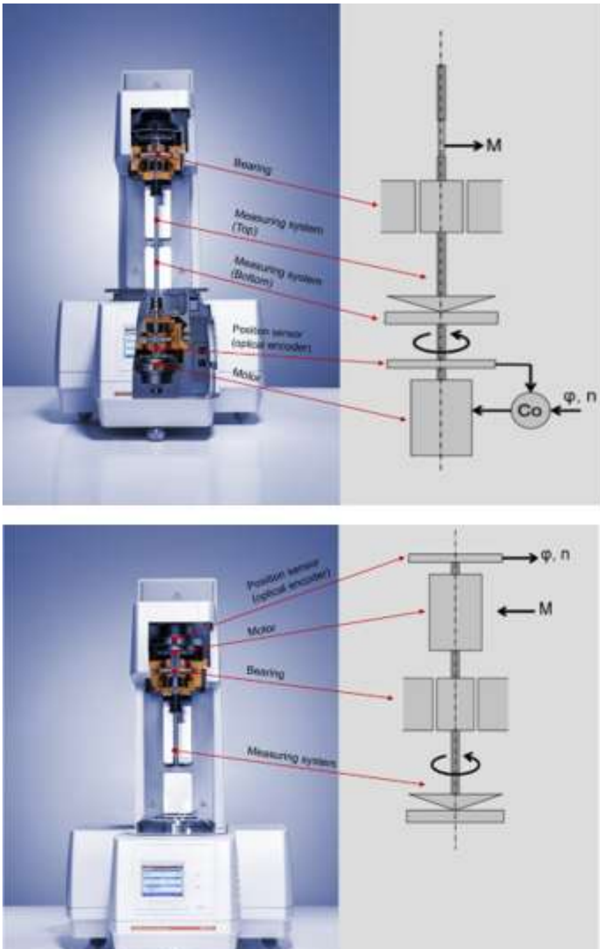


Figure 34 Examples of Rheometers [121,122]

CAPILLARY RHEOMETER

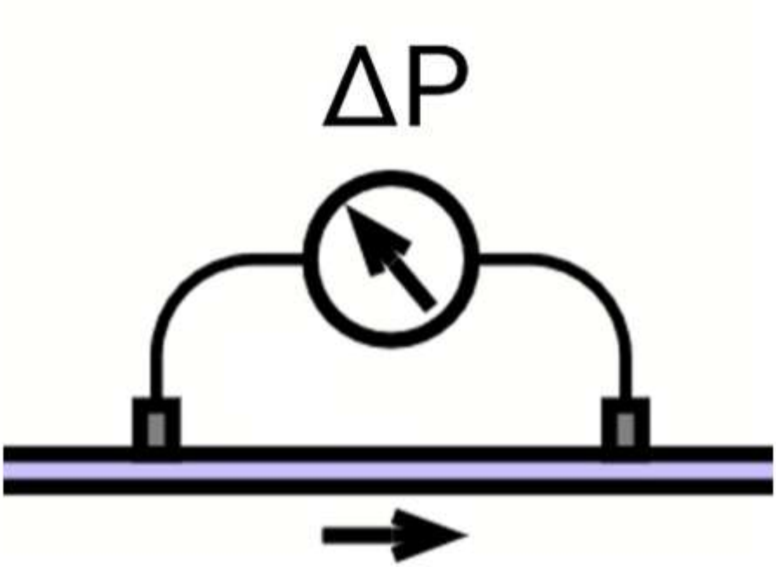
Capillary rheometer is pumping fluids into a tube and measure the pressure drops or changes and then confined this information with thermodynamics to define the shear stress and viscosity. It measures viscosity at high shear rates (>1000 s^{-1}), relevant for extrusion. Figure 35 shows the basics of the capillary rheometer. The pressure-drop over the capillary is measured as the sample is pumped through. From thermodynamics, the shear stress directly relates to the pressure drop. The flow characteristic, laminar preferred because of developed characteristics as defined as smooth and calm, Fluid layers of the cylinders sliding along the common axis defined in Figure 35 and results in well-defined shear rate on the inner wall of the capillary. This method has an advantage for having a closed loop systems and evaporation is not a problem for this application. The huge deformation in the flow characteristic of the sample conserves or prevents the flow from concerning complex rheological characteristics as oscillational effects, vortexes etc...

Capillary rheometer can assess effects like die swell and flow instabilities in nozzle-like geometries. It is also important factor for nozzle design or extrusion processes.

The using sample is another important factor. If the measuring system is difficult to clean after measurements, a parallel-plate or cone-plate system should be used instead. Cylinder measuring systems are relatively difficult to clean.

There are disposable systems available for all measuring system types. These can be disposed of along with the sample or cleaned separately. This is required for samples which undergo a curing process.

On the other hand, capillary rheometer has no such kind of difficulties for cleaning process.



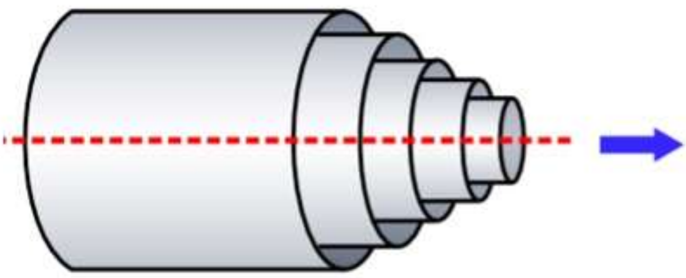


Figure 35 Capillary Rheometer Basics [121,122,123]

Shear dependent viscosity used the high-pressure capillary rheometer, already pointed out and the schematic is depicted in Figure 36, a reservoir that puts the pallets in, capillary as the barrel and pressure is going on the reservoir. Piston extrudes sample at the controlled speed and temperature from a barrel reservoir through a given capillary die while the pressure is sampled continuously at the entrance to the die. Constant controlled piston speed is equal to the constant shear rate. The higher the viscosity is resulted in the higher resistance to flow out of the barrel and higher is the recorded pressure which is related to shear stress. For step by step the piston is going down, and it moves to controlled speed and kept as a constant temperature screw the capillary and have different diameters and pressure is meshed at the entrance to the die and then when having the constant and controlled speed-controlled shear rate. The viscosity is given with the shear stress over the shear rate. That controlled parameters are the piston speed, distance or displacement and the temperature. At shared schematic is about both the rotational rheometer in a previous episode with the same principle with rotational rheometer about the shear between the plates that the upper plates moved and at the same principle, shearing virtual layer by layer in capillary rheometer that actually turned up rotated and this is how to get the shear profile. Speed at the wall is zero and we say no slip, and in the center is the maximum with the assumption of laminar flow and incompressibility. And control these parameters meshed the pressure and the relations sets as given;

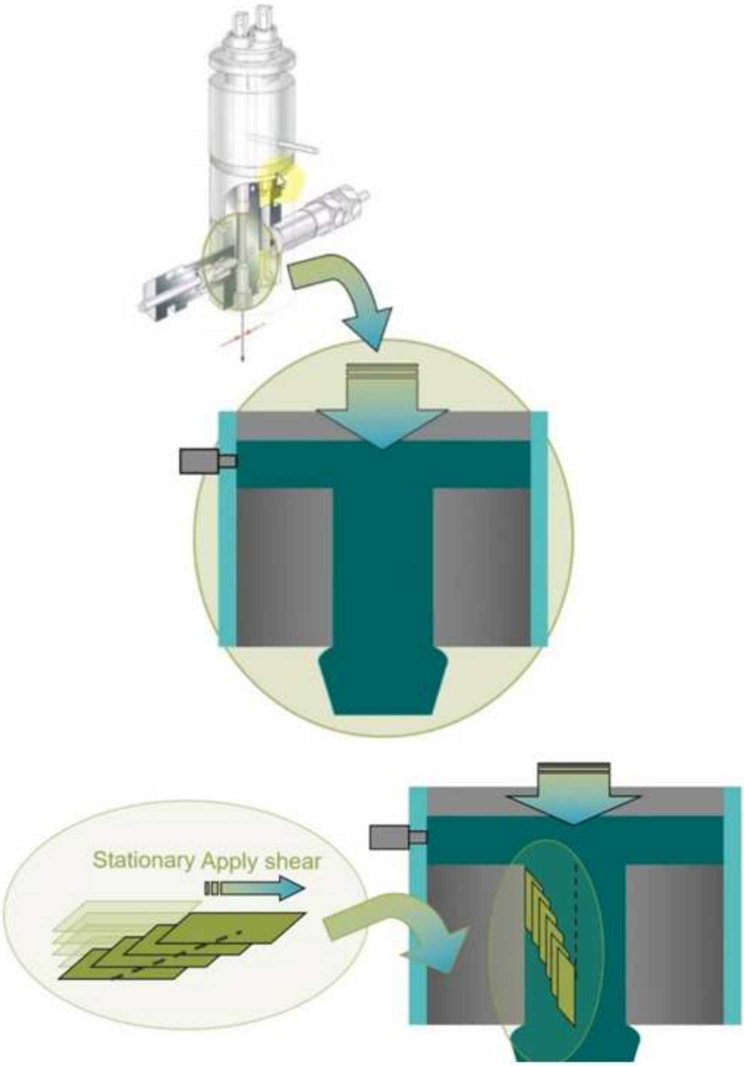


Figure 36 Capillary rheometer

$$\text{Viscosity} = \frac{Shear\ Stress}{Shear\ Rate} \text{ or } \eta = \frac{\tau}{\dot{\gamma}}$$

Pressure to shear stress:

$$\tau_w = \frac{(P_0 - P_L)R}{2L}$$

Displacement to shear rate:

$$\dot{\gamma_w} = \frac{4Q}{\pi R^3}$$

In all process the temperature needs to be constant because of the temperature dependency of rheological behavior.

How is the measurement really work and what is the analysis of it is the next point? We use different piston speeds and that applies different shear rate on the sample dependent on the die diameter that we can switch the capillaries out. For each applied piston speed, a shear rate (dependent on die diameter) is applied on the sample. Then once we reach the equilibrium pressure recorded. An equilibrium pressure is recorded for each piston speed to calculate a shear viscosity related graphical representation gathered using the formulations above. Eight data analysis is given in Figure 37.

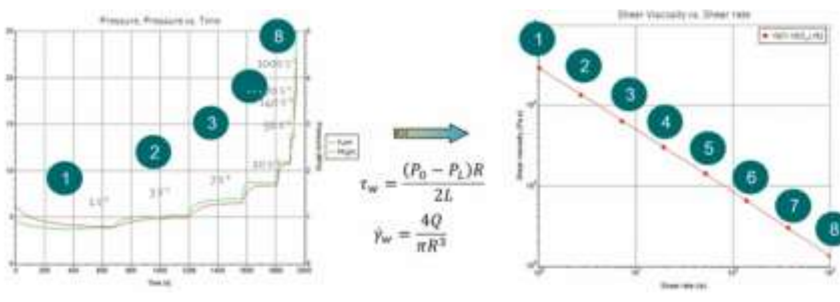


Figure 37 Measurement and analysis

IN-LINE RHEOLOGICAL CONTROL

In traditional AM processes, material behavior is often assumed to be constant once characterized offline. However, in-process changes in temperature, humidity, shear rate, or material degradation can cause real-time variations in rheology, leading to; uneven extrusion or clogging, poor interlayer adhesion, inaccurate geometry, surface roughness or porosity. Hence, real-time monitoring and control of rheological properties is critical for process stability, print quality, adaptive control material certification (especially in bio-printing or aerospace)

In-line control of rheological characteristics in additive manufacturing (AM) especially in material extrusion (e.g., FDM) and direct ink writing (DIW) is an emerging and crucial area of research and development. Rheological properties like viscosity, shear thinning, yield stress, and thixotropy play a vital role in determining printability, shape retention, and final part quality.

IN-LINE CONTROL METHODS

Key rheological parameters include viscosity vs. shear rate (flow curve), yield stress storage (G') and loss modulus (G''), viscoelastic behavior, thixotropy and time-dependent shear behavior are desired to monitor.

In-line Viscometers/Rheometers which are capillary rheometers in order to measure pressure drop through a nozzle to infer viscosity, torsional or rotational rheometers used with miniaturized and integrated in-line, but rare due to size/complexity, ultrasound-based rheometer for generally non-invasive technique to infer flow properties.

Extruder Pressure Monitoring to measure back pressure or extrusion force which works with changes in pressure under constant conditions correlate to viscosity. Sensor-based systems in the extruder head can provide indirect rheological feedback.

Thermal and Optical Sensing with Infrared (IR) thermography in order to monitors temperature, indirectly controlling viscosity in thermoplastics and Optical Coherence Tomography (OCT) or high-speed cameras in order to visualize for layer uniformity and surface defects, indirectly indicating rheology issues.

Machine Learning and Sensor Fusion data clearance from various sensors (temperature, pressure, force, visual) can be fused and analyzed using Machine Learning (ML) to infer and predict rheological changes and adjust process parameters in real time.

In-Line Control Mechanisms;

Adaptive nozzle temperature uses for adjusting heater zones in response to changing viscosity.

Variable extrusion speed/pressure uses in order to maintain constant flow rate despite viscosity shifts.

Material feed rate control

Closed-loop feedback systems in order to combine sensor inputs with control algorithms to maintain optimal rheology.

Special considerations by material type are taken consideration with thermoplastics (FDM application) viscosity highly dependent on temperature and shear; nozzle-based pressure and temp control works well. Viscous inks (DIW application) yield stress and thixotropy are critical; pressure sensors and optical monitoring are key. Bio inks which require tight control due to cell viability; low-shear in-line systems + real-time rheological feedback is essential.

Applications and research directions is summarized as smart extrusion heads with embedded sensors, real-time process correction using AI, in-line certification of printable inks (esp. for pharmaceutical, biomedical AM), integration with digital twins for predictive control.

There are specific challenges and resist requirements for in-line controlling rheology in application which are given in the Table 8.

Table 8 Challenges for in-line monitoring rheology

Challenge	Why It Matters in AM
Non-Newtonian behavior	Many inks/pastes show shear thinning, yield stress, thixotropy—so viscosity is highly dependent on shear rate and time. Control must deal with variable shear in the nozzle and flow path.
Temperature sensitivity	Especially thermoplastics: slight temperature variations lead to large changes in melt viscosity. Heat losses, heater zones, environmental changes matter.
Time delays / residence time	Material takes time to heat, to be extruded, to respond to control changes. These delays affect feedback design.
Measurement noise and sampling rate	Sensor readings (pressure, temperature, flow) may be noisy, slow, or have lag. High fidelity required especially for fast printing or fine features.
Disturbances / variability	Material feed variation, moisture content, filler particles, nozzle wear, clogging, slippage, etc. All these can cause rheology to drift.
Feedback actuation constraints	What can you adjust in real time? Heater temps, extrusion pressure, nozzle geometry (rare), pump rate, print speed, etc. The possible control "knobs" limit what you can stabilize.

Sensing and monitoring hardware is given with

Table 9.

Table 9 Sensing and monitoring hardware for in-line rheology control

Sensor type	What it measures / how used	Pros	Cons / Practical Issues
Pressure transducers / load cells (in nozzle, in flow path)	Melt pressure in nozzle or upstream; can infer shear stress, or back-pressure that reflects viscosity changes. E.g. modified nozzle with pressure sensor.	Directly senses what matters; relatively fast; can be compact.	Need calibration; entrance / exit effects; must correct for shear heating; high pressure ranges; mechanical stability; drift; cost.
Thermocouples / RTDs / temperature sensors	Melt temperature; zones along extruder; ambient temperature. Combined with pressure / flow to infer viscosity.	Temperature is a big driver of rheology; usually easy to measure.	Response time; spatial non-uniformity; heater control resolution; thermal inertia.
Flow / volumetric rate sensors / filament encoders	Measures how much material is entering or leaving (extruder screw speed, filament feed vs. slip, etc.). Key for calculating shear rate, which combined with pressure gives viscosity.	Essential to compute viscosity (since viscosity = stress/shear rate) or detect anomalies (slip, motor skipping).	Calibration; resolution; sampling; slip & backlash; mechanical hysteresis.
Optical / imaging sensors (high speed camera, laser displacement / layer profile)	Detect strand width, surface quality, shape distortion. While not directly measuring viscosity, deviations imply rheological issues. E.g. in bio-printing, laser scanning after deposition.	Can catch geometric errors or deposition defects; non-contact.	Complex image processing; occlusion; lighting; slower; may lag (~ deposition then scanning).
Rheometer inserts / micro-slit or capillary rheometers in-line	Like embedding a small rheometer in the flow path (e.g. micro-slit rheometer) to directly measure flow curve under process conditions. Example: micro-slit rheometer for filament production.	Provides rich rheological data; closer to "ground truth" under process.	Adds complexity; may increase pressure drop; thermal control needed; can have long measurement paths / delays; limited to lab/dev environments currently.

There are specific control strategies and developed algorithms summarized as given Table 10

Table 10 Sensing algorithms for in-line monitoring

Strategy / Algorithm	Description	Advantages	Disadvantages / Where It Works Best
PID control (Proportional-Integral-Derivative)	Use error between measured variable (e.g. melt pressure, inferred viscosity) and set point to adjust actuator (e.g. extrusion pressure, temperature, feed rate).	Simpler; well-understood; relatively easy to implement; many AM machines already support PID loops (for temp, flow, etc.).	May struggle with delays, nonlinearities, non-Newtonian behavior; tuning can be tricky; oscillations or overshoot; may not handle multi-variable interactions well.
Feedforward control	Use model-based predictions (e.g. given temperature, shear rate, etc.) to pre-set or adjust parameters, anticipating some variability, rather than just reacting.	Helps offset predictable disturbances; can reduce lag.	Requires accurate models; material behavior must be well characterized; if unexpected disturbances occur, feedforward alone is insufficient.
Model Predictive Control (MPC)	Use a predictive model of rheology, flow dynamics, temperature, etc., to	Can handle multivariable systems; anticipate effects; deal with constraints; better performance	More computationally intensive; demands good models; needs fast enough sensors; more

Strategy / Algorithm	Description	Advantages	Disadvantages / Where It Works Best
	optimize control inputs over a horizon, considering constraints.	under multiple disturbances.	complex tuning; latency matters.
Observer / State Estimation	For states you can't measure directly (e.g. internal temperature profile, interface between molten vs solid, viscosity inside nozzle etc.), use observers (Extended Kalman Filters, Luenberger, PDE observers) to estimate them from sensor data.	Allows richer control; reduce sensor cost; improve stability.	Model accuracy critical; noise; cost.
Adaptive Control	Adjust controller parameters on the fly to account for drift, changes in material, nozzle wear, etc.	Good for systems that change over time.	Risk of instability; more complexity; needs robust algorithms.
Event / Disturbance-Triggered Control	Detect anomalies like	Helps safety, reliability; avoids	Need good detection; may interrupt print;

Strategy / Algorithm	Description	Advantages	Disadvantages / Where It Works Best
	clogging, filament slip, material feed variation, etc., triggering special corrective action (slow down, purge, pause, etc.).	accumulating errors.	may degrade throughput.

Some documented systems where in line or in process rheological monitoring or control have been used. In line rheological monitoring of fused deposition modeling: Coogan & Kazmer (2019) inserted a custom pressure transducer and thermocouple into an FDM printer nozzle, as well as a filament encoder. From pressure + flow + temperature they computed viscosity inside the nozzle during printing. They compared to off line rheometry and found good agreement. [141].

Micro slit rheometer for filament production: A micro extrusion line with a slit rheometer in line was used to monitor melt flow during filament making. They validated the in line rheological data vs off line devices, for LDPE and cyclic olefin copolymer [142].

Force Controlled Printing: Recent work (2024) where extrusion force (measured in real time via load cell) is used as feedback to control material flow, to maintain desired line width, adapt to disturbances (bed leveling, etc.). This shows that even a simpler rheological proxy (extrusion force) can be effective [143].

Numerical modeling in DIW in this study simulate how changing parameters (nozzle velocity, material inlet velocity, nozzle diameter, gap to substrate) influence distortions of strands, cross section shape, etc., to help predict and tune process for shape fidelity. While not full real time feedback, these support control design [144].

Multivariable real time control of viscosity curves in non-additive manufacturing settings (e.g. mixing plants, chemical production) shows feasibility for controlling target rheological curves by adjusting flows of components; using model predictive control, managing disturbances. Though not AM, techniques are transferable in many respects [145].

How an AM system with real in line rheological control might be architected. There is a generic "blueprint" you could adapt.

Sensors & Data Acquisition

Pressure sensor in or just upstream of nozzle

Temperature sensors: melt temp, barrel zones, ambient

Flow / feed measurement: filament encoder, screw speed, pump flow

Optional: layer height / strand width via optical / laser measurement

Signal Conditioning & Filtering

Noise suppression (electrical, thermal)

Compensation for known geometrical or entrance exit corrections (e.g. Bagley correction for capillary flow, corrections for non-Newtonian flow)

Calibration so that readings map reliably to shear stress / shear rate / viscosity

Model / Rheological Laws

Use a constitutive model (e.g. Cross WLF, power law, Herschel Bulkley, or others) that describes how viscosity depends on temperature, shear rate, potentially pressure.

If yield stress or viscoelastic effects are important, include those.

Control & Feedback Loop

Define what you control: e.g., maintain viscosity within bounds, control a "critical point" on the flow curve, maintain consistent strand width or layer deposition rate.

Control inputs might include: extruder temperature, heater zone setpoints; feed rate / screw motor speed; nozzle movement speed; pressure / pump control; cooling rates.

Use a feedback control algorithm (could be PID, MPC, adaptive control) that takes sensor data, computes error against desired rheological variable, then adjusts actuators.

Delay / Latency Compensation

Account for delays: thermal lag, residence time, response of heater zones, etc. Possibly use predictors, observers, or models that include delay.

Calibration / Learning

Offline material characterization: get the flow curves, temperature dependence, etc., to parameterize the models.

Online adaptation: detect drift, model mismatch, and adjust model parameters (e.g. via regression, machine learning) for better fit over time.

Safety / Anomaly Detection

Detect unexpected conditions: pressure spikes (partial clog), feed slip, material jams, moisture variation, anomalies in output geometry.

Trigger corrective actions: reduce extrusion, pause, purge, adjust temperature, etc.

Practical Considerations & Limitations, Potential Research / Implementation Directions

While it's quite powerful, implementing in line rheological control is not trivial. Some of the practical limits. Cost is the beginning, high precision sensors, custom nozzles, temperature control, optical systems, and fast data acquisition can add tremendous cost. Complexity is the second one, more components means more failure modes, maintenance, calibration needed. Material variety is the third one for each new material, you often need characterization (off line) to get model parameters; behavior may change with batch, moisture, fillers, etc. Tradeoff between speed and accuracy is the fourth one with faster printing tends to exacerbate shear heating, lag; more precise control may require slower operations or more sophisticated hardware. Scalability is the fifth one with for large prints, long extruder/nozzle paths, large residue times, etc., delays and thermal gradients get worse. Sensor robustness is the sixth one for sensors in the hot melt path endure harsh thermal, mechanical stress; long term drift is possible. Some ideas (and perhaps gaps) for advancing in line rheological control in AM as following;

- Embedded mini rheometers: Further miniaturization to fit in nozzle or very close to nozzle, with minimal pressure drop, to get more immediate rheology measurement.
- Machine Learning / Data Driven Models: Use learning to map sensor signals (pressure, temperature, flow, vibration) to rheological state, perhaps reducing dependency on full physical model. Could adapt over batches.
- Multi sensor fusion: Combine pressure, temperature, optical / imaging sensors, perhaps acoustic sensors, to get richer state estimation.

- Real time control of yield stress / thixotropy: Many inks (bio inks, ceramic pastes) have time dependent behavior; controlling not only instantaneous viscosity but structural rebuild after shear, etc., is challenging.
- Standards for "printability" rheological metrics: Define which rheological properties map well to print outcomes; find minimal necessary parameters to measure in line.
- Robust control under disturbances: e.g. nozzle wear, clogging, environment variability, feedstock variability; develop disturbance detection and compensation.
- Real world applications: Scaling lab demonstrations to industrial scale, maintaining reliability and cost effectiveness.

MECHANICAL PROPERTIES EVALUATION

Evaluating the **mechanical properties** of plastic 3D-printed parts is essential to ensure that the parts meet the necessary performance, reliability, and durability requirements for their intended applications. The mechanical properties are typically evaluated through a series of standardized tests that assess various characteristics such as strength, flexibility, impact resistance, and durability. Here's a detailed look at the main mechanical properties typically evaluated in plastic 3D printing and the methods used for testing:

KEY MECHANICAL PROPERTIES FOR PLASTIC 3D PRINTING

Tensile Strength

- **Tensile strength** is the maximum stress a material can withstand while being stretched or pulled before breaking. This property is critical for understanding how a 3D-printed part will behave under tension.

- **Testing Method**: Tensile testing is commonly done using a **universal testing machine** (UTM), where the specimen is subjected to a gradually increasing tensile force until it breaks. The result is typically reported in megapascals (MPa).
- **Standard Test Methods**:
  - **ASTM D638**: Standard test method for **tensile properties of plastics**.
  - **ISO 527**: Similar to ASTM D638, but this standard is for a broader range of polymer materials.

Flexural Strength

- **Flexural strength** refers to the ability of a material to resist deformation under load when bent. This property is important for parts that will experience bending or flexing during use.
- **Testing Method**: The flexural test involves placing a specimen on two supports and applying a load at the center. The deflection and the force at which the material breaks or deforms are measured.
- **Standard Test Methods**:
  - **ASTM D790**: Standard test method for **flexural properties of unreinforced and reinforced plastics**.
  - **ISO 178**: Similar to ASTM D790, used for testing the flexural properties of plastics.

Impact Resistance

- **Impact resistance** measures how well a material absorbs energy when subjected to a sudden impact or shock. This property is crucial for parts that are subjected to dropping, striking, or other high-impact conditions.
- **Testing Method**: The most common test for impact resistance is the **Izod impact test**, where a specimen is notched and struck with a pendulum hammer to see how much energy is required to break the material.
- **Standard Test Methods**:
    - **ASTM D256**: Standard test method for **impact resistance of plastics**.
    - **ISO 180**: Similar to ASTM D256 but for global standardization.

Elongation at Break

- **Elongation at break** is the percentage increase in length a material experiences before it breaks when subjected to tensile stress. It indicates the material's ductility (ability to deform without breaking).
- **Testing Method**: Elongation is measured during a tensile test, typically when the specimen is stretched until it fractures.
- **Standard Test Methods**:
    - **ASTM D638** (for plastic materials).
    - **ISO 527** (for polymer materials).

Hardness

- **Hardness** refers to a material's resistance to indentation, scratching, or wear. This property is essential for determining how resistant a 3D-printed part is to surface damage.
- **Testing Method**: A hardness test is often done using a **Shore durometer**, where a standardized indenter is pressed into the surface of the material, and the hardness is quantified based on the depth of the indentation.
- **Standard Test Methods**:
  - **ASTM D2240**: Standard test method for **rubber property—durometer hardness**.
  - **ISO 868**: Standard for **determining the hardness of plastics**.

Compression Strength

- **Compression strength** is the ability of a material to resist deformation when compressed. This is critical for parts that will bear loads or weight vertically.
- **Testing Method**: Similar to tensile testing but with compression forces. The material is compressed between two plates, and the resulting stress-strain curve is evaluated.
- **Standard Test Methods**:
  - **ASTM D695**: Standard test method for **compressive properties of rigid plastics**.
  - **ISO 604**: Similar to ASTM D695 for testing the compressive strength of plastics.

Shear Strength

- **Shear strength** refers to the ability of a material to resist forces that cause the internal structure to slide against itself. It is essential for parts that will experience shear forces, such as during assembly or bonding.
- **Testing Method**: Shear testing can be done by applying a force parallel to the surface of the material and measuring the resistance until failure occurs.
- **Standard Test Methods**:
  - **ASTM D732**: Standard test method for **shear strength of plastics**.

ADDITIONAL CONSIDERATIONS FOR PLASTIC 3D PRINTING

- **Orientation Dependence**: One key factor that influences mechanical properties in plastic 3D printing is the **build orientation**. Parts printed along different axes (e.g., Z-axis vs. X/Y axes) will have different properties, especially for Fused Deposition Modeling (FDM) and similar technologies. It's important to evaluate how part orientation affects strength, stiffness, and overall performance.
- **Material Variability**: The mechanical properties of 3D-printed parts can vary widely depending on the type of plastic used (e.g., PLA, ABS, PETG, Nylon, etc.) and the printer settings (e.g., layer height, infill density, and print speed). Material suppliers often provide data sheets that include mechanical property information, but these properties can differ when parts are 3D printed.

- **Post-Processing**: Some 3D printing methods (such as SLA or SLS) require post-processing (e.g., curing, cleaning) that can further influence the final mechanical properties. Testing should account for these effects.

MECHANICAL PROPERTY TESTING IN PLASTIC AM (STANDARDS OVERVIEW)

Here are some **relevant standards** for testing mechanical properties in plastic 3D printing:

- **ASTM F3184**: Guide for testing and reporting mechanical properties of polymer parts made using additive manufacturing.
- **ASTM D638**: Standard for **tensile properties**.
- **ASTM D256**: Standard for **impact resistance** testing.
- **ISO 527**: Standard for **tensile testing** of plastic materials.
- **ISO 178**: Standard for **flexural testing**.

Evaluating the mechanical properties of plastic 3D-printed parts is crucial to ensure they perform well under expected operating conditions. By using standardized tests such as tensile, impact, flexural, and compression tests, manufacturers can gain a clear understanding of how the material will behave in real-world applications. It's also important to consider factors like print orientation, material choice, and post-processing, as they can all influence the mechanical properties of the final printed part.

Nonuniformity and **post-processing** are two critical aspects of additive manufacturing (AM) that can significantly influence the quality, performance, and appearance of 3D-printed parts.

Conductivity of heat is validated with temperature sensors placed between the layers and test samples shown in

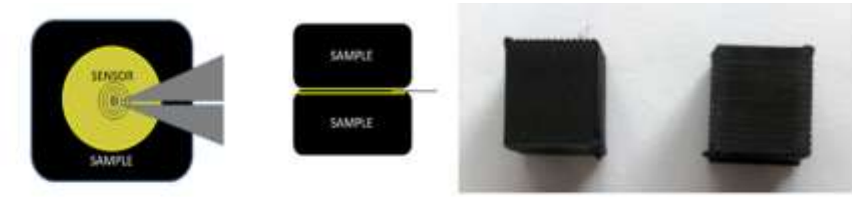


Figure 38. In particular test mechanism is given a chance to measure the structural health of the main parts of the aviation components as a coupon level.

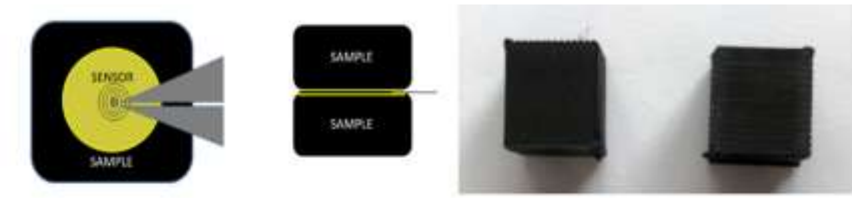


Figure 38 Conductivity Test samples [9]

Rinaldi et all studied that the test set up results 3D printed samples thermal conductivity error states are wider than the injection molded samples. These conductivity error states resulted mainly from the voids in the layers of printed part [9]. Results clearly showed that 3D printed samples have more voids in production and comparatively bad results in error rate and conductivity shown in Figure 39.

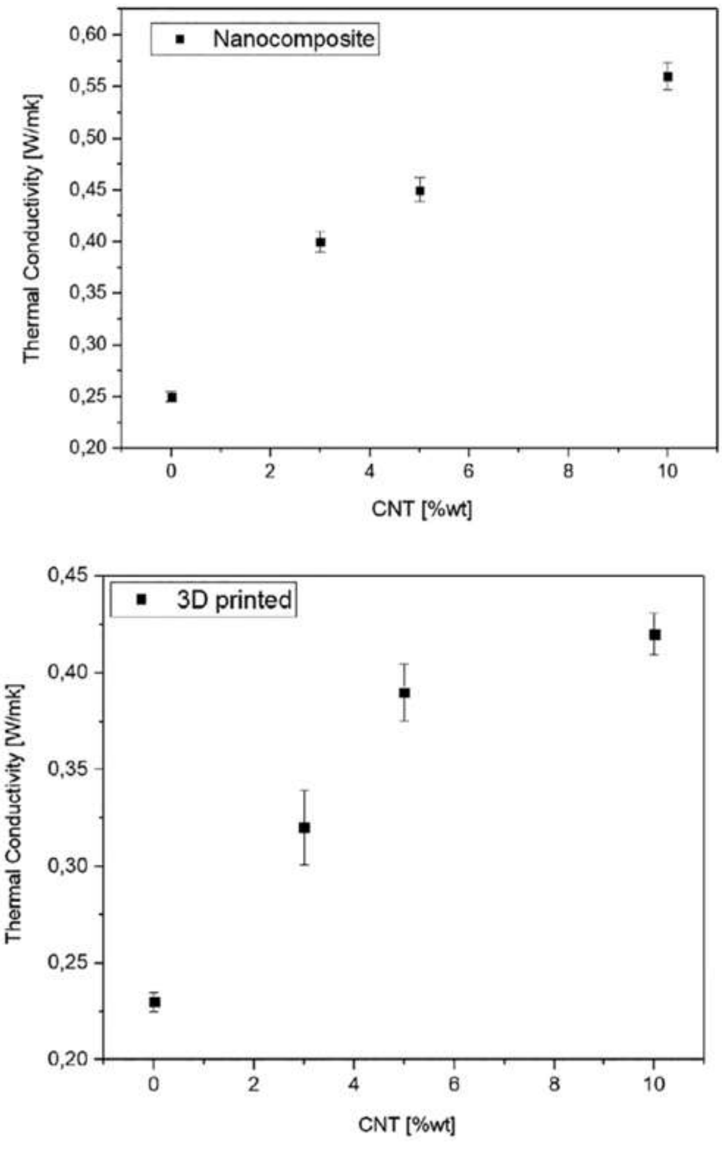


Figure 39 Results Comparing 3D Printed and Injection Molding Process [9]

To be conclude, comparison with the injection molding processed nanoscale enhanced PEEK samples with FFF printed ones, there are differences in the thermal conductivity and the strength values. FFF printed ones has lower thermal conductivity due to the gaps in the samples during the process. In order to eliminate the effects of the voids inside the sample, compression molding after process could be implied. It is similar with working principle of the hot isostatic pressing process used in metal additive manufacturing. Process parameters optimization and holistic approach is applied in the process with in-situ monitoring of the process with real time processed closed loop control systems and very high-resolution cameras. It is enabled to change the process parameters in some part of the second or millisecond or in real time depending on the feedbacks. Another future perspective of FFF technique is automatically nanoparticle additives insertion in the nozzle before the extrusion from the nozzle tip and control the homogeneity of the additives in real time.

RELATED STANDARDS

Plastic additive manufacturing (AM), often referred to as 3D printing, has specific standards and guidelines to ensure consistency, quality, safety, and interoperability. Various organizations have developed standards for the materials, processes, testing methods, and safety requirements related to plastic AM. Here are some of the most important standards:

ASTM F42 (Committee on Additive Manufacturing Technologies)

The **ASTM F42** committee is one of the most influential in developing standards for additive manufacturing. This committee has developed several critical standards, including:

- **ASTM F2792**: This standard defines terminology related to additive manufacturing and is essential for clarifying the language used in the industry. It outlines key terms like "additive manufacturing," "3D printing," and more.
- **ASTM F3184**: A standard guide for testing and reporting mechanical properties of plastic parts produced by additive manufacturing. It specifies test methods for tensile strength, impact resistance, and other mechanical properties.
- **ASTM F3055**: This standard provides guidelines for the qualification and certification of 3D-printed medical devices, specifically for plastic materials.

ISO/ASTM 52900-2021

This is an international standard that defines **general principles** for additive manufacturing, including the classification of processes, materials, and systems. It focuses on **additive manufacturing processes** and includes guidelines for terms and definitions.

ISO/ASTM 52910-2020

This standard focuses on **design for additive manufacturing** (DfAM). It helps designers, engineers, and manufacturers understand how to design parts that are optimized for 3D printing, specifically for plastics. The document provides guidelines on how to adjust designs based on material and manufacturing constraints to improve part performance.

ISO 9001:2015

Though not specific to 3D printing, **ISO 9001** for quality management systems (QMS) is essential for ensuring that additive manufacturing processes meet the required quality standards. In plastic AM, this would involve ensuring that materials and parts are manufactured consistently, with traceability and proper documentation.

ISO/ASTM 52915

This standard specifies the **file format for additive manufacturing**. It standardizes the file format for exchanging 3D model data between software and machines, ensuring compatibility between different systems and processes. For plastic additive manufacturing, this is critical for ensuring that parts are accurately built according to the design.

ISO/ASTM 52950

This standard is related to **additive manufacturing terminology and testing for metal-based additive manufacturing**, but it also includes some overlap with plastic AM, particularly regarding print accuracy, testing methods, and material certifications.

ISO 17025:2017

ISO 17025 pertains to the general requirements for the competence of testing and calibration laboratories. In plastic additive manufacturing, it is often used to certify labs that perform tests on materials, parts, and products, ensuring the accuracy and reliability of testing equipment and processes.

SAFETY STANDARDS (UL 2904 and UL 94)

- **UL 2904**: A standard that addresses the **safety of 3D printing materials**. This standard test and evaluate the health impacts of 3D printing materials during use and ensures materials used in additive manufacturing meet specific safety guidelines.

- **UL 94**: This standard defines the flammability ratings of materials, including plastics, and is important in ensuring that 3D printed plastic parts meet necessary fire safety standards.

MATERIAL-SPECIFIC STANDARDS

Several standards address specific types of plastic materials used in additive manufacturing. These standards can help guide manufacturers in selecting appropriate materials based on performance requirements:

- **ISO 52903-1**: This standard defines requirements for **polymer-based materials** used in AM.
- **ASTM D638**: Standard test method for the tensile properties of plastics, often applied to plastic parts produced by 3D printing.
- **ISO 18752**: For **thermoplastic elastomers**, which are often used in flexible 3D printing applications.

TEST METHODS

Various standards exist for testing the properties of plastic parts made via additive manufacturing. These test methods can address everything from **mechanical properties** (e.g., tensile strength, elongation at break, and impact resistance) to **thermal properties** (e.g., heat deflection temperature). Key standards include:

- **ASTM D3039**: Standard test method for **tensile properties of composite materials**.
- **ISO 75**: Standard for **heat deflection temperature** testing.

The standards governing plastic additive manufacturing aim to ensure that the parts are produced with high quality, safety, and reliability. These standards address a variety of aspects, from material specifications and design principles to testing methods and safety considerations. Staying up to date with these standards is crucial for manufacturers looking to adopt 3D printing technologies for production or prototyping.

If you're working in this space, it's important to reference the appropriate standards for your specific application to ensure compliance and optimal results.

QUALITY CONTROL FOR PLASTIC APPLICATIONS

Achieving perfect quality in additive manufacturing parts is a multi-faceted process that involves optimizing materials, equipment, process parameters, design choices, environmental factors, and post-processing techniques. By paying attention to these conditions, manufacturers can ensure that AM parts meet the required standards of dimensional accuracy, mechanical properties, surface finish, and overall performance. Regular calibration, proper material selection, precise process control, and post-processing are key to maximizing the potential of 3D printing technologies and ensuring high-quality output.

Quality control (QC) for **plastic parts** produced via **additive manufacturing (AM)** is also critical, especially as 3D printing with plastic materials has become increasingly popular across various industries, including automotive, medical, consumer goods, aerospace, and more. QC for plastic AM parts involves a combination of material selection, process monitoring, and post-processing techniques to ensure that the printed parts meet the desired performance standards. This paper highlights the challenges associated with quality control in additive manufacturing, focusing on factors like dimensional accuracy, surface finish, and process repeatability in both metal and plastic AM [70].

Plastic 3D printing includes technologies such as **Fused Deposition Modeling (FDM)**, **Stereolithography (SLA)**, **Selective Laser Sintering (SLS)**, and **Material Jetting**, each requiring different QC methods. Below is an overview of the quality control processes and standards specifically for plastic parts in additive manufacturing applications.

Quality control for plastic parts in additive manufacturing (AM) is a multi-step process that requires careful monitoring from material selection to post-processing. Key areas of QC include ensuring proper material properties, monitoring the printing process, performing post-processing treatments, conducting mechanical and dimensional testing, and utilizing non-destructive testing methods to ensure the part's integrity. Effective QC ensures that the final part meets the necessary functional, aesthetic, and safety requirements.

By implementing a comprehensive quality control plan, manufacturers can enhance the performance and reliability of plastic parts produced through additive manufacturing, making them suitable for a wide range of applications

MATERIAL QUALITY CONTROL

- **Material Specifications**: The first step in QC is ensuring that the plastic material (such as PLA, ABS, Nylon, PETG, or specialty resins) complies with the required specifications.
    - **Chemical Composition**: The resin or filament used must meet the composition standards for the intended application, including any industry-specific requirements for food contact, medical, or aerospace use.

   - **Moisture Content**: Some plastics are hygroscopic (e.g., Nylon and ABS) and can absorb moisture from the air, affecting the print quality. QC involves checking for excess moisture, which can cause issues like warping or poor bonding between layers.
   - **Melt Flow Rate**: For thermoplastics, the melt flow rate is a critical factor that influences the ease of extrusion and layer adhesion.

PRE-PROCESSING CONTROL

- **Printability**: The design of the plastic part should be optimized for additive manufacturing. This includes factors such as:
   - **Part Orientation**: The orientation of the part on the build platform can impact its strength, surface finish, and ease of post-processing.
   - **Support Structures**: Supports are often required for overhangs and complex geometries. Proper design of support structures ensures ease of removal and minimizes the impact on the final part quality.
- **Material Preparation**: In some cases, plastic filaments or powders need to be dried before printing to avoid issues caused by moisture absorption (e.g., in Nylon or PVA filaments).

IN-PROCESS MONITORING AND CONTROL

- **Layer-by-Layer Monitoring**: Since AM parts are built up layer-by-layer, it's essential to monitor the deposition process to ensure proper layer bonding and part alignment.

    - **Extruder Temperature**: Ensuring that the nozzle temperature matches the material specifications is crucial for achieving optimal flow and adhesion.
    - **Bed Temperature**: Maintaining a consistent heated bed temperature ensures proper adhesion of the first layer and helps reduce warping.
    - **Print Speed**: Controlling print speed ensures that each layer bonds well with the previous one, preventing weak spots or delamination.
- **Real-Time Monitoring**: Some advanced 3D printers feature in-process monitoring systems such as:
    - **Thermal Cameras**: To monitor the print bed and nozzle temperatures in real-time, preventing overheating or underheating issues.
    - **Optical Cameras**: To detect layer misalignment or print failures (e.g., material clogging, extrusion issues).
    - **Laser Scanning**: Can be used to monitor the part's dimensional accuracy during printing.

POST-PROCESSING CONTROL

- **Surface Finishing**: Plastic parts often require post-processing to improve their surface finish, especially for parts with visible layer lines. Methods such as:
    - **Sanding**: Manual or automated sanding can smooth the surface of plastic parts.
    - **Vapor Smoothing**: In the case of materials like ABS, vapor smoothing can be used to enhance the surface finish by exposing the part to acetone vapors, which melt and smooth the surface.

- **Painting or Coating**: Adding coatings or paints can provide additional durability, aesthetic appeal, or resistance to environmental factors.

- **Heat Treatment**: In some cases, post-processing may involve heating the part to relieve internal stresses or improve mechanical properties (e.g., annealing for certain plastic materials like Nylon or PETG).

NON-DESTRUCTIVE TESTING (NDT)

Non-destructive testing (NDT) is useful for verifying the quality of plastic parts, particularly when they have complex geometries that make traditional testing difficult. Common NDT methods include:

- **Visual Inspection**: Checking for obvious surface defects, layer misalignment, or signs of material inconsistencies.
- **Ultrasonic Testing**: While less common than in metal AM, ultrasonic testing can sometimes be used to detect internal defects such as voids or weak bonding between layers in thick-walled plastic parts.
- **X-ray or CT Scanning**: For parts with complex internal structures, CT scanning can be used to detect internal defects like voids, internal porosity, or inconsistencies in layer adhesion.
- **Tensile Testing**: For plastic parts subjected to mechanical loading, tensile testing measures the strength and elongation properties of the material.
- **Thermography**: Uses infrared cameras to identify heat signatures and detect issues with layer adhesion and thermal uniformity during or after the print.

MECHANICAL TESTING

- **Tensile and Compression Testing**: Essential for parts subject to mechanical stresses. Tensile testing evaluates the material's resistance to stretching, while compression testing checks how well the material handles compression forces.
- **Impact Testing**: Plastic parts, especially those used in automotive or consumer applications, may be subject to impact testing (e.g., Charpy or Izod tests) to evaluate their toughness.
- **Hardness Testing**: Shore hardness testing (e.g., Shore A or D) is commonly used for flexible or rigid plastic parts to determine their resistance to indentation.
- **Fatigue Testing**: Parts that undergo repetitive loading, such as plastic gears or joints, require fatigue testing to evaluate how they perform over time under cyclic stresses.

DIMENSIONAL CONTROL

- **Part Dimensions**: Ensuring that the printed plastic part meets the exact specifications is crucial. Dimensional tolerance can be affected by factors like print speed, layer height, and cooling rates. Measuring the final part with tools like calipers, micrometers, or 3D scanners ensures that it fits into the intended assembly or application.
- **Geometric Accuracy**: For parts that require high precision, techniques like **laser scanning** or **structured light scanning** can be used to compare the physical part against the original CAD model to check for any deviations.

CERTIFICATION AND COMPLIANCE

- **Industry Certifications**: Similar to metal parts, plastic parts used in certain industries (e.g., medical, aerospace, automotive) may need to meet specific certification standards. These include:
    - **ISO 13485** for medical devices (ensures part safety and effectiveness).
    - **IATF 16949** for automotive parts (ensures part reliability and repeatability).
    - **FDA Compliance** for parts used in food, drug, or medical applications.
- **RoHS (Restriction of Hazardous Substances)**: Compliance with RoHS standards is essential for plastic parts used in electronics to ensure they do not contain hazardous materials such as lead, mercury, or cadmium.

TRACEABILITY AND DOCUMENTATION

- **Material Traceability**: Just like metal AM, maintaining a traceable record of the material batch (e.g., filament or resin) used in each print run ensures consistency and helps identify issues if they arise during production.
- **Process Documentation**: Recording the settings used for each print, such as temperature, layer height, and print speed, is crucial for troubleshooting and maintaining consistent results over time.

CONCLUSION AND FUTURE PERSPECTIVES

Additive manufacturing can help benefit the supply chain in industry having a steady and reliable source of spare parts is essential. At the same time most of the spare part costs are due to storage and logistics loaded the company finance. Additive manufacturing enables spare parts due to be manufacturing lightning, fast on demand, eliminating tool and storage costs and also increase efficiency since production occur with exactly the right number of parts.

The review discusses the environmental impacts of additive manufacturing, including energy consumption, material waste, and the lifecycle impact of 3D-printed metal and plastic parts [72], another one This paper systematically reviews the sustainability issues related to additive manufacturing, focusing on energy efficiency, material sourcing, recycling, and sustainable practices in both metal and plastic AM [73].

The future perspectives of **additive manufacturing (AM)** are exciting and hold tremendous potential for transforming a wide range of industries. Here are some key trends and future directions for AM:

MATERIALS INNOVATION

- **New Materials**: A major focus of future AM research is expanding the range of materials available for 3D printing. In addition to traditional polymers, metals, and ceramics, future developments could include **biodegradable materials**, **multi-material composites**, **smart materials**, and **materials with embedded sensors**.
- **Material Properties and Performance**: Advancements in material science will improve the **mechanical properties** (e.g., strength, durability, flexibility) of printed parts, making AM a more viable solution for industries like aerospace, automotive, and medical devices.

SUSTAINABILITY AND CIRCULAR ECONOMY

- **Sustainable Manufacturing**: As environmental concerns grow, additive manufacturing has the potential to play a significant role in the **circular economy**. AM allows for more efficient material use with minimal waste, as parts are built layer by layer based on digital designs, reducing material waste compared to traditional subtractive manufacturing.
- **Recycling**: AM could enable the recycling of used or scrap materials into new products, helping industries reduce their carbon footprint. Companies are exploring **closed-loop recycling systems** in 3D printing where old 3D-printed parts are reused as raw material for new products.

AUTOMATION AND INTEGRATION WITH AI AND MACHINE LEARNING

- **Automation**: As AM moves toward mass production, it will likely be integrated with **automated systems** for seamless operation. Future systems could involve **robotic arms**, **automated material handling**, and **smart factory setups**, where 3D printers are integrated with other machines on the factory floor to streamline production.
- **Artificial Intelligence (AI)** and **Machine Learning (ML)**: AI will be used to **optimize designs**, **predict part performance**, and **automate quality control**. Machine learning algorithms can help refine printing processes, improving efficiency, speed, and quality, while also minimizing the need for human intervention.

CUSTOMIZATION AND ON-DEMAND MANUFACTURING

- **Mass Customization**: One of the most significant advantages of additive manufacturing is the ability to produce **customized products**. In the future, AM will continue to evolve in industries like **healthcare**, where products like implants, prosthetics, and dental devices can be personalized for individual patients.
- **On-Demand Manufacturing**: AM can enable on-demand production at the point of need, reducing the need for large-scale inventory storage and minimizing transportation costs. This will be particularly beneficial for industries like aerospace, defense, and automotive, where parts can be produced just-in-time or in remote locations.

FASTER PRODUCTION AND SCALE-UP

- **Speed**: Although AM has traditionally been slower than conventional manufacturing methods, advances in **printing speed** (e.g., multi-laser systems, faster layer deposition) will enable faster production rates. New AM technologies such as **continuous liquid interface production (CLIP)** and **ultrafast laser sintering** have the potential to drastically reduce production times.
- **Scalability**: Traditionally, AM has been seen as a **prototype** or **low-volume manufacturing** technology. However, future innovations could enable AM to scale up for **mass production**. The use of **multi-material and multi-process AM** could make it suitable for high-volume production while maintaining cost-effectiveness.

DISTRIBUTED MANUFACTURING

- **Decentralized Production**: AM allows for **decentralized manufacturing**, meaning that products can be designed and printed at various locations rather than centralized factories. This could have profound impacts on **supply chain management**, reducing transportation costs, lead times, and reliance on a single point of failure in the supply chain.
- **Localized Manufacturing**: Localized 3D printing hubs could emerge, where products are produced closer to the end customer, reducing environmental impact and enabling more agile responses to market demands.

BIOFABRICATION AND MEDICAL APPLICATIONS

- **Bioprinting**: One of the most futuristic aspects of AM is **bioprinting**—the ability to print living tissues and potentially organs. While current bioprinting is primarily used for **tissue engineering** and **drug testing**, future advancements could lead to the creation of **functional organs**, offering solutions to the organ shortage crisis.
- **Personalized Medicine**: AM will continue to revolutionize personalized healthcare, from custom **prosthetics** and **implants** to tailored **drug delivery systems** and **surgical planning**. Doctors may use 3D printing to create personalized medical devices or anatomical models to improve surgeries and patient outcomes.

INDUSTRY-SPECIFIC ADVANCES

- **Aerospace**: AM has already made significant strides in the aerospace industry, where it's used for creating lightweight, high-performance components. In the future, AM could enable the production of entire aircraft components or even whole small planes, reducing weight, cost, and fuel consumption.
- **Automotive**: The automotive industry is embracing AM for both **prototyping** and **production of complex parts**. In the future, AM could be used for producing **lightweight parts**, **functional prototypes**, and custom components that improve vehicle performance.
- **Construction**: Large-scale 3D printing in construction is also gaining traction. Future developments could see entire **houses or buildings** being printed on-site, reducing labor costs and material waste.

ADVANCES IN 3D PRINTING TECHNOLOGIES

- **Hybrid Systems**: Future 3D printers may combine different manufacturing processes, such as **additive** and **subtractive** methods, to create **hybrid systems**. These systems will allow for more complex and precise manufacturing with multiple material types.
- **Printing on a Larger Scale**: The development of large-format 3D printers, particularly in sectors like construction and aerospace, will enable the production of large-scale objects. Some companies are already experimenting with printing houses, bridges, and even vehicles.

REGULATORY AND STANDARDS DEVELOPMENT

- **Regulation and Standards**: As AM becomes more widespread, there will be a need for stricter **regulations** and **standards** to ensure quality, safety, and consistency, especially in industries like aerospace, medical devices, and automotive. Organizations such as ASTM International and ISO will continue to play an important role in developing these guidelines.
- **Intellectual Property (IP)**: As 3D printing technology becomes more accessible, **IP** concerns regarding the protection of designs and the ownership of digital files will need to be addressed through stronger protections and legal frameworks.

NEW BUSINESS MODELS

- **Distributed Design and Manufacturing Networks**: The future could see the rise of **digital manufacturing platforms**, where designers, engineers, and manufacturers can collaborate to create customized products. This would allow smaller companies to offer high-quality, custom products without needing large-scale manufacturing facilities.
- **Subscription and Pay-Per-Print Models**: Business models that leverage **cloud-based AM services** could evolve, allowing businesses to produce products on demand and pay per print. This would lower upfront costs and enable smaller businesses to access AM capabilities.

CONCLUSION

The future of **additive manufacturing** is promising, with numerous **technological advancements** and **application areas** poised to transform industries. As new materials, faster printing technologies, and more sustainable practices emerge, AM will become even more integrated into **mainstream manufacturing**. It holds the potential to make manufacturing more agile, sustainable, and personalized, with wide-ranging applications in **medicine**, **aerospace**, **automotive**, **construction**, and **consumer products**. However, challenges in standardization, intellectual property protection, and scalability remain, and these will need to be addressed for AM to realize its full potential.

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