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Educating Undergraduate Students in Theory, Practice and Experience in Additive Manufacturing

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Approach in Educating Undergraduate Students in Theory and Practice of Additive Manufacturing

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Abstract

The growing need for ever-changing customer demand pressurizes the manufacturing industry to look for a flexible and fast-changing small-volume production system. As a result, additive manufacturing (AM) is one of the fastest-growing methods of changing a 3D design model to a 3D product without any process planning method. The process is commonly called 3D printing technology and has found extensive applications in areas such as automotive, architecture, manufacturing, aerospace, thermal, flexible electronics, medicine, fashion, retail, and sports. A major aspect of 3D printing technology is its ability to produce parts which are not possible by traditional manufacturing techniques. The students at any level can be introduced to the technology and understand the theoretical aspects in coordination with practice in the laboratory. The paper examines the underlying 'rules' that help companies take full advantage of additive manufacturing technologies. The paper also examines the guidelines for the design of additive manufacturing with in-depth discussion of design constraints. These guidelines are discussed with the view of creating light weight parts, efficient heat exchangers and components for aerospace industries. The paper investigates different influencing variables including the variation due to density and porosity. Other modeling equations that influence the additive process are examined, which include energy balance equations for melting and vaporization. Post processing of 3D additive components is also critical to the outcome of overall process as it impacts resulting surface quality, total cycle time and cost.

Keywords: Additive process, Design guidelines for AM, Equations for AM

Introduction

The Industrial Revolution, spanning from the late 18th to mid-19th century, marked a transformative shift in global economies and societies. Originating in Britain, it saw the mechanization of production processes, powered by steam engines and later electricity. Innovations like the spinning jenny, steam locomotives, and factories propelled mass production, leading to urbanization and a shift from agrarian to industrial economies. The revolution brought about profound social, economic, and technological changes, impacting labor, transportation, and communication. As it spread globally, the Industrial Revolution laid the foundation for modern industrialized societies and significantly altered the course of human history [1, 2].

The transition from the Industrial Revolution to conventional manufacturing marked a shift from predominantly mechanized and centralized production to more traditional and decentralized methods. Following the mass industrialization era characterized by steam power and assembly lines, conventional manufacturing emphasizes smaller-scale, artisanal, and locally based production [3, 4]. This shift often involves a return to manual craftsmanship, reduced reliance on heavy machinery, and a renewed focus on personalized and sustainable manufacturing practices. The move towards conventional manufacturing reflects a desire for more human-centric, environmentally conscious, and community-oriented approaches in response to the social and environmental impacts of large-scale industrialization [5, 6].

Additive Manufacturing (AM) emerged in the 1980s as a revolutionary technology for creating objects layer by layer from digital models. Its roots trace back to stereolithography invented by Chuck Hull in 1983. The 1990s witnessed the expansion of AM applications into various industries. As patents expired, technology became more accessible, fostering innovation. By the 2000s, diverse materials and techniques emerged, enhancing AM's capabilities. Today, it plays a crucial role in rapid prototyping, custom manufacturing, and even aerospace applications. Additive manufacturing continues to evolve, shaping the future of manufacturing with its versatility and efficiency.

Additive manufacturing (AM) offers several advantages over conventional manufacturing methods. Primarily, AM enables complex and intricate designs with minimal material waste, as it builds objects layer by layer [7, 8]. This customization capability is particularly beneficial for producing intricate prototypes and personalized components [9, 10]. Additionally, AM allows for the integration of multiple parts into a single, consolidated structure, reducing assembly requirements [11-13]. Technology facilitates rapid prototyping, accelerating product development cycles. AM's flexibility in using diverse materials enhances the production of unique and specialized items. It is particularly advantageous for low-volume and on-demand manufacturing, reducing the need for large-scale production setups [14]. Furthermore, additive manufacturing supports design iterations without expensive tooling adjustments. Although traditional manufacturing methods are well-established, additive manufacturing's efficiency, flexibility, and capability for innovative design make it a compelling choice, especially in industries demanding customization, quick prototyping, and resource-efficient production processes [15-17]. Over the years, it evolved across industries, impacting aerospace, healthcare, and automotive sectors [18 - 21]. Advances in materials and processes have expanded their applications, fostering innovation and customization. Today, additive manufacturing stands as a transformative force, revolutionizing traditional manufacturing methods and shaping the future of production [22, 23].

Rationale for Additive Manufacturing in Engineering Education

Exposing students to various additive manufacturing processes is crucial for their education and career readiness. It cultivates a diverse skill set, enabling them to adapt to evolving technologies in fields like engineering and design. Understanding different processes, such as Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS), enhances problem-solving abilities and creativity [24, 25]. Exposure to diverse techniques fosters critical thinking, enabling students to choose the most suitable method for specific projects. This comprehensive knowledge prepares them for the demands of a dynamic job market, encouraging innovation and a deeper understanding of the rapidly advancing field of additive manufacturing. AM employs a variety of materials, energy sources, and techniques to create objects layer by layer from digital models. Materials range from thermoplastics and metals to ceramics and biomaterials. Thermoplastics, like ABS and PLA, are prevalent in desktop 3D printing, ULTUM 1010 & 9085 using FDM based Fortus industrial machine, and metals such as titanium and aluminum are used in industrial applications [26, 27].

AM techniques include Fused Deposition Modeling (FDM), which deposits thermoplastic filaments layer by layer and Stereolithography (SLA), employing liquid photopolymer cured by UV light. Selective Laser Sintering (SLS) and Electron Beam Melting (EBM) uses a laser and electron beam to fuse powdered materials like nylon or metal.

Why Additive Manufacturing: Ten Principles that can benefit Industries [28]

Principle one: Manufacturing complexity is free. In traditional manufacturing, the more complicated an object's shape, the more it costs to make. On a 3-D printer, complexity costs the same as simplicity, Figure 1. Fabricating an ornate and complicated shape does not require more time, skill, or cost than printing a simple block. Free complexity will disrupt traditional pricing models and change how we calculate the cost of manufacturing things.

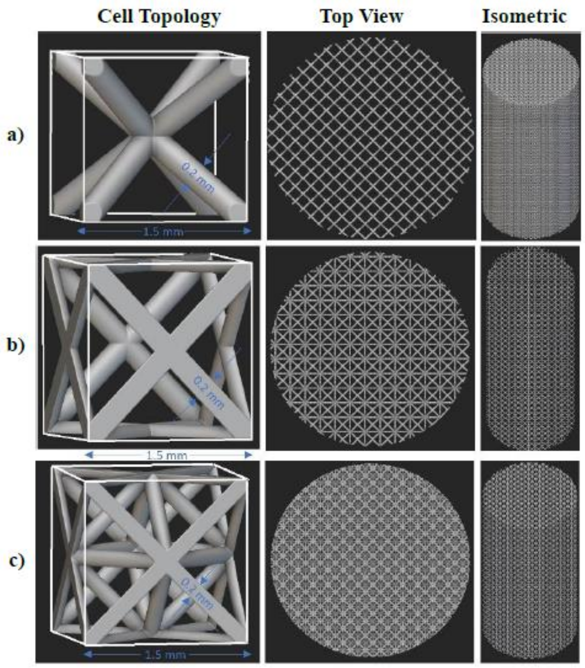


Figure 1: Complex geometry design and optimization in Lattice structure [30]

Principle two: Variety is free. A single 3-D printer can make many shapes. Like a human artisan, a 3-D printer can fabricate a different shape each time. Traditional manufacturing machines are much less versatile and can only make things in a limited spectrum of shapes. 3-D printing removes the over- head costs associated with re-training human machinists or re-tooling factory machines. A single 3-D printer needs only a different digital blueprint and a fresh batch of raw material.

Principle three: No assembly required. 3-D printing forms interlocked parts. Mass manufacturing is built on the backbone of the assembly line. In modern factories, machines make identical objects that are later assembled by robots or human workers, sometimes continents away. The more parts a product contains, the longer it takes to assemble and the more expensive it becomes to make. By making objects in layers, a 3-D printer could print a door and attached interlocking hinges at the same time, no assembly required. Less assembly will shorten supply chains, saving money on labor and transportation; shorter supply chains will be less polluting.

Principle four: Zero lead time. A 3-D printer can print on demand when an object is needed. The capacity for on-the-spot manufacturing reduces the need for companies to stockpile physical inventory. New types of business services become possible as 3-D printers enable a business to make specialty -- or custom -- objects on demand in response to customer orders. Zero-lead-time manufacturing could minimize the cost of long-distance shipping if printed goods are made when they are needed and near where they are needed.

Principle five: Unlimited design space. Traditional manufacturing technologies and human artisans can make only a finite repertoire of shapes. Our capacity to form shapes is limited by the tools available to us. For example, a traditional wood lathe can make only round objects. A mill can make only parts that can be accessed with a milling tool. A molding machine can make only shapes that can be poured into and then extracted from a mold. A 3-D printer removes these barriers, opening up vast new design spaces. A printer can fabricate shapes that until now have been possible only in nature.

Principle six: Zero skill manufacturing. Traditional artisans train as apprentices for years to gain the skills they need. Mass production and computer-guided manufacturing machines diminish the need for skilled production. However traditional manufacturing machines still demand a skilled expert to adjust and calibrate them. A 3-D printer gets most of its guidance from a design file. To make an object of equal complexity, a 3-D printer requires less operator skill than an injection molding machine does. Unskilled manufacturing opens up new business models and could offer new modes of production for people in remote environments or extreme circumstances.

Principle seven: Compact, portable manufacturing. Per volume of production space, a 3-D printer has more manufacturing capacity than a traditional manufacturing machine. For example, an injection molding machine can only make objects significantly smaller than itself. In contrast, a 3-D printer can fabricate objects as large as its print bed. If a 3-D printer is arranged so its printing apparatus can move freely, a 3-D printer can fabricate objects larger than itself. A high production capacity per square foot makes 3-D printers ideal for home use or office use since they offer a small physical footprint.

Principle eight: Less waste by-product. 3-D printers that work in metal create less waste by-product than traditional metal manufacturing techniques do. Machining metal is highly wasteful as an estimated 90 percent of the original metal gets ground off and ends up on the factory floor. 3-D printing is more wasteless for metal manufacturing. As printing materials improve, "Net shape" manufacturing could be a greener way to make things.

Principle nine: Infinite shades of materials. Combining different raw materials into a single product is difficult using today's manufacturing machines. Since traditional manufacturing machines carve, cut, or mold things into shape, these processes can't easily blend together different raw materials. As multi-material 3-D printing develops, we will gain the capacity to blend and mix different raw materials. New previously inaccessible blends of raw material offer us a much larger, mostly unexplored palette of materials with novel properties or useful types of behaviors.

Principle ten: Precise physical replication. A digital music file can be endlessly copied with no loss of audio quality. In the future, 3-D printing will extend this digital precision to the world of physical objects. Scanning technology and 3-D printing will together introduce high resolution shapeshifting between the physical and digital worlds. We will scan, edit, and duplicate physical objects to create exact replicas or to improve the original.

Principle of Operation of Additive Manufacturing Processes

1. FUSED Deposition Modeling (FDM)

FDM process revolves around the filaments derived from various thermosetting plastics, with a particular emphasis on bio-degradable polymers like PLA, which serve as crucial components in scaffold structures, as shown in Figure 2 [29]. The filaments undergo a transformation into a semi-solid state and are directed onto the platform using an extruder nozzle of varying sizes. Primarily, the extruder follows the x and y directions, guided by the g-code produced by slicing software, to execute the printing process.

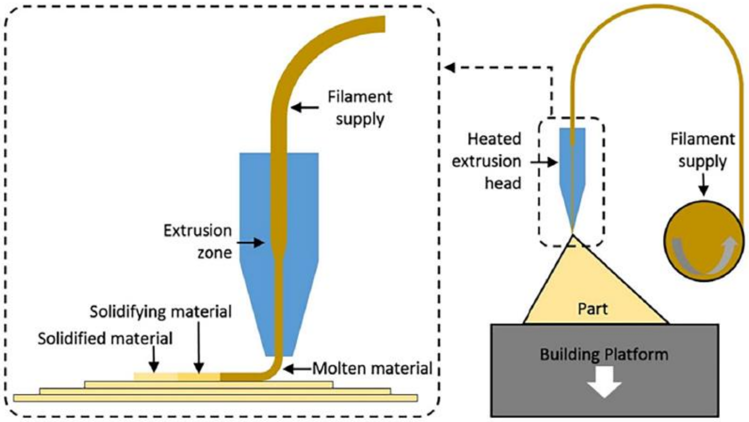
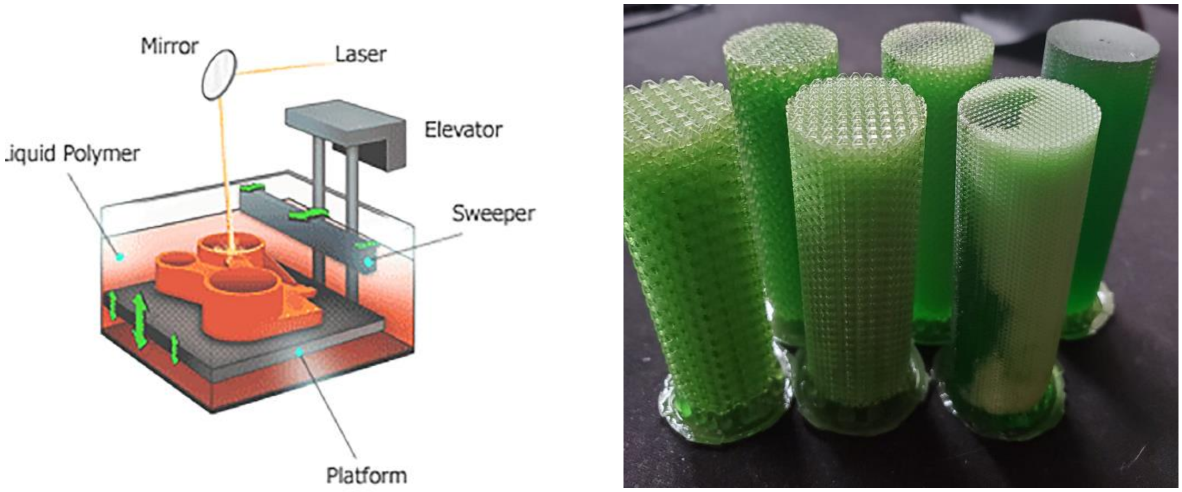


Figure 2. Schematic representation of Fused Deposition Modeling

2. Stereolithography (SLA)

SLA apparatus constructs layers of resin through the utilization of scanning lasers or light projectors. In this process, photopolymers within the resin are cured by exposure to light. The formation of each layer involves the precise tracing of light or laser beams across the resin surface on the build platform, as shown in Figure 3 [29]. Subsequently, as the layer is completed, the build platform descends into the resin, and a coater is employed to even out the resin layer to match the specified thickness outlined in the input parameters.



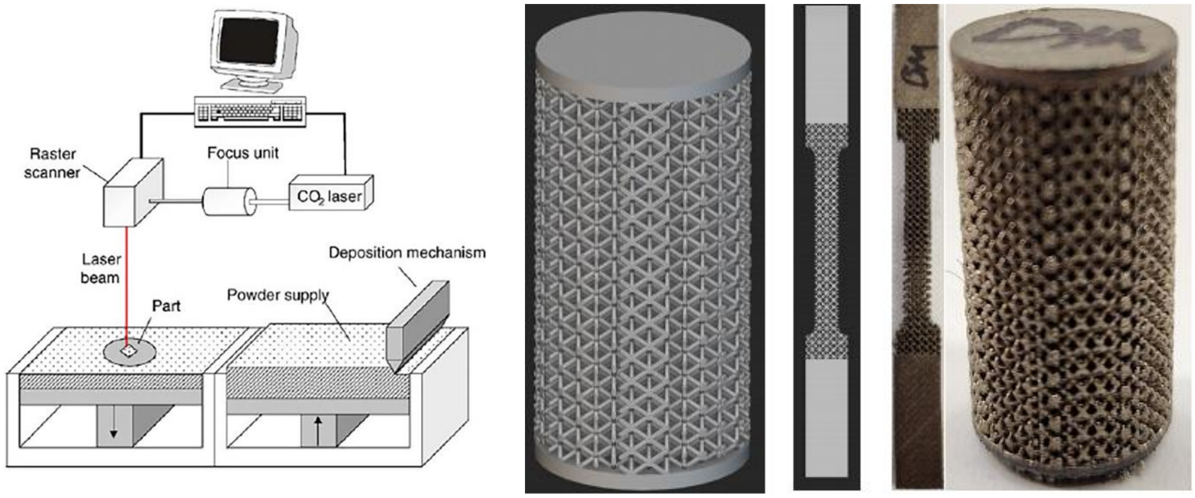
a) SLA Schematic representation **b) Lattice structure made using SLA produced at UDC**

Figure 3 SLA process and lattice structure produced using SLA.

3. Selective Laser Sintering (SLS)

SLS is a cutting-edge technology that employs a laser as the energy source to sinter powder, creating a single part through a layer-by-layer methodology, as shown in Figure 4a [29] and lattice structure produced using SLS process is shown in Figure 4b [30]. Sintering and melting, often denoted as SLS and SLM, respectively, essentially refer to the same process. In the case of SLS using a CO2 laser, the entire procedure unfolds within a confined chamber. To prevent external light interference during printing, the chamber is sealed off, given that the laser serves as the binding source.

The powder is loaded into a vat for the initial layer spreading. The process initiates with the laser sintering of the powder layer on the platform. Subsequently, the platform undergoes movement in the z-axis, and fresh powder is dispersed over the preceding layer for further sintering. This sequential layering and sintering process persists until the entire object is successfully fabricated.



a) b)

Figure 4: Schematic representation of SLS and Intricate product design and actual maraging steel product of lattice structure produced at UDC CAMSTAR lab [30].

4. Electron Beam Melting (EBM)

EBM utilizes a vacuum chamber and a heated platform to facilitate the incremental melting of raw material layer by layer, employing an electron beam as the energy source. The raw material, which can exist in either wire or powder form, undergoes a meticulous process of transformation within this controlled environment, leading to the gradual construction of the desired object through successive layers, as shown in Figure 5 [29].

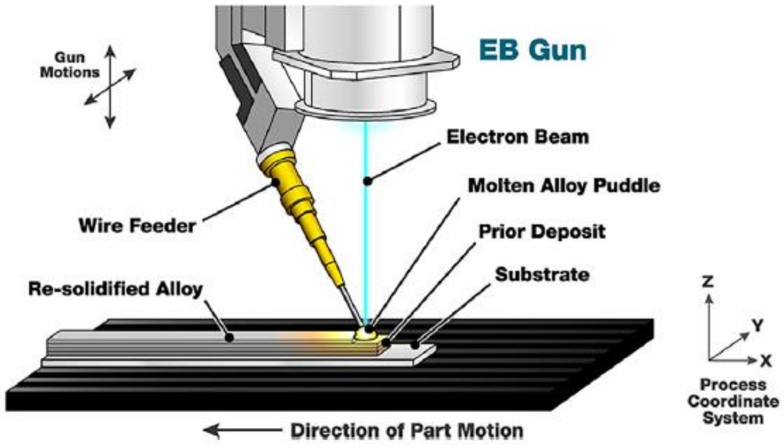


Figure 5 Electron Beam Melting process

Energy sources vary; FDM relies on electrical energy to heat and extrude filaments, SLA employs UV light for photopolymerization, and SLS uses lasers for sintering. Binder Jetting involves selectively depositing a liquid binder onto powder layers [31].

These diverse materials, energy methods, and techniques contribute to AM's versatility, enabling applications in aerospace, healthcare, automotive, and beyond. The continuous development of new materials and processes enhances efficiency, precision, and range of applications, making AM a transformative force in modern manufacturing.

Metal AM is pivotal in modern industry. It is essential due to its ability to produce complex and customized metal components with improved efficiency, reduced waste, and enhanced design freedom [32-34]. Its ability to produce intricate, strong, and customized metal parts has revolutionized sectors like aerospace and medical [35, 36]. The precision, efficiency, and material variety in metal 3D printing make it a cornerstone, driving innovation and reshaping traditional manufacturing processes.

The evolution of metal AM has seen advancements in materials like titanium, stainless steel, and nickel alloys, broadening its applicability in aerospace, healthcare, and automotive industries [37]. Technologies such as Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM) have emerged, offering precise layer-by-layer metal deposition [38]. Research and development have focused on optimizing parameters, improving surface finishes, and increasing the range of printable alloys [39]. The continuous evolution of metal AM methods has elevated its role from prototyping to full-scale production, fostering innovation and reshaping manufacturing paradigms in the pursuit of efficiency, sustainability, and tailored solutions.

Governing equation for creating AM component.

Achieving a successful product through AM involves considering various factors to optimize the process. The quality of the AM produced parts depends on several variables that can be monitored in metal 3D printing process. The general governing equations are the conservation of mass, momentum and energy-based continuum formulas [40]. But some of the prominent variables can be expressed in a simple equation shown in equation (1) [41]. These variables are laser power, scan speed, hatching distance and layer thickness. The relationship between energy density, laser power, scan speed, hatching distance and layer thickness can be expressed as,

$$E = \frac{P_L}{v_S \times h_S \times s} \tag{1}$$

Where, E is Energy Density J/mm^3, PL is the laser power, v_s the scan speed, h_s the hatching distance and *s* the layer thickness.

The governing equation shown in Equation (1) can guide us to systematically control the parameters in metal 3D printing process. One of the issues that need to be controlled in metal AM is porosity. Porosity is inversely a proportional relation between volume energy density, as shown in equation (2) [41]. Figure 6 depicts a schematic representation of the AM process, illustrating the various influencing parameters.

$$\varepsilon = k.\frac{1}{E} = k.\left(\frac{P_L}{v_S \times h_S \times s}\right) \tag{2}$$

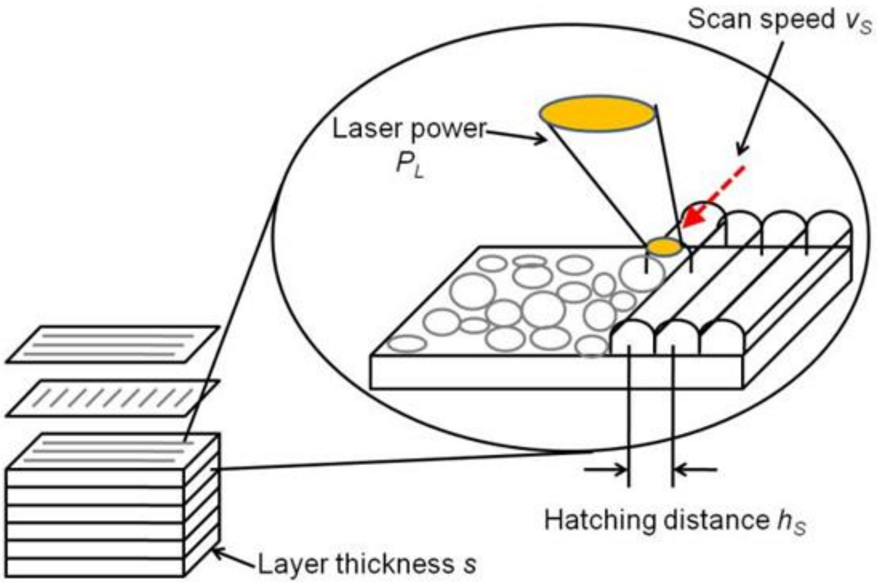


Figure 6 Schematic Representation of AM process [41]

Recent Trends in AM for Aerospace Industry

The aerospace sector continually seeks lightweight materials and innovative fabrication methods to lower costs by reducing aircraft weight, thereby optimizing fuel efficiency. Among the critical components explored within this industry are those associated with engines. These include augmenters, combustors, compressor stators, gearboxes, drive and turbine shafts, ducts, fan and turbine frames, fan stators, and diffuser cases. High-value components like casings and vanes, along with rotating parts such as blades, rotors, and blade-integrated disks, are of particular interest. Materials such as Inconel, titanium, and aluminum hold significance in the aerospace industry's pursuit of these objectives.

AM is increasingly favored in the aerospace industry due to its ability to address challenges associated with the timely procurement of certain components, such as bulkheads, ribs, and rib web structures, particularly in small quantities. Additionally, components crafted from costly and challenging-to-machine materials like aluminum, nickel, or titanium alloys, sourced from die, forgings, or plate stocks, are driving the adoption of AM technologies. Major motivating factors for AM in the aerospace industry are:

- The AM process reduces raw material usage, machining operations and lead times.
- Less raw material requirement, ability to machine thinner and smaller quantities components.
- Ability to repair the damaged components.
- Ability to locate the defects, inspect the repair, restore the part to its full mechanical capabilities.

Example of Additive Manufacturing Research Project

One example of a typical research project is the creation of a heat exchanger. Conventional manufacturing techniques have a limitation in producing parts of a complex design of geometries. AM techniques provide flexibility of design and allow fabricating novel devices. Heat exchangers are a valuable part of most heating and cooling appliances and systems at home and in the workplace. One of the challenges in heat exchanger fabrication is the creation of micro channels. The removal of high heat flux from microelectronic circuitry is one of the most important applications of microchannels. When the channel dimensions are decreased, heat transfer coefficients become large which will improve the heat transfer. Figure 7 shows how complex the design of heat exchangers was fabricated through AM techniques.

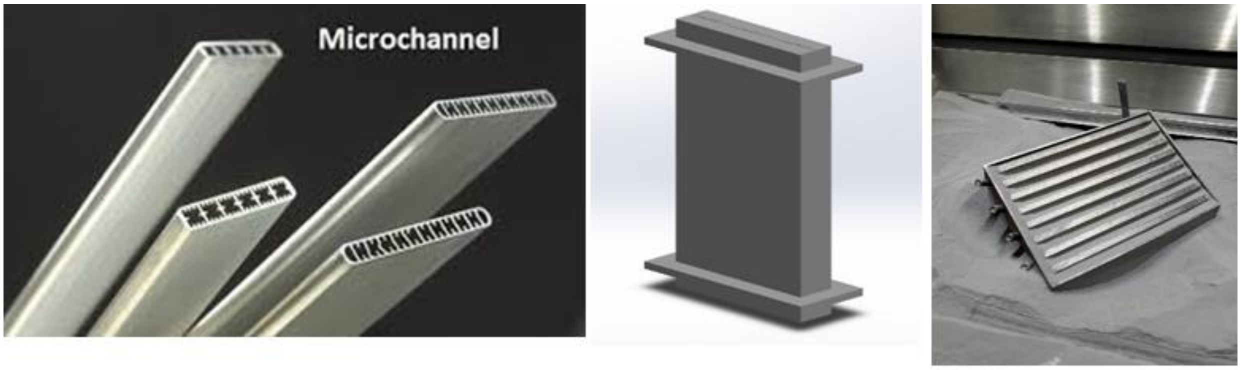
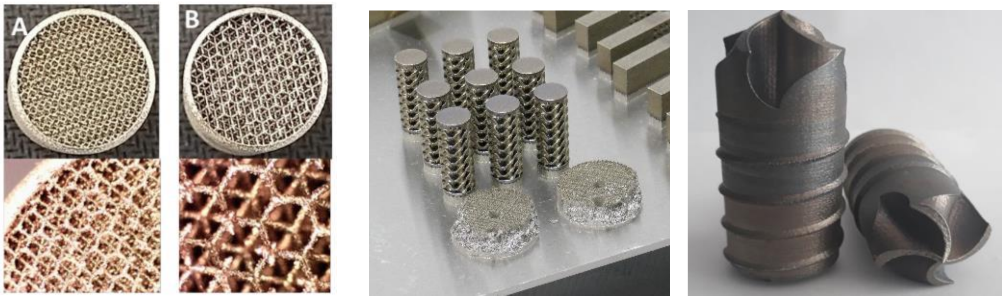


Figure 7. Additively Manufactured Heat Exchangers for improved thermal performance



AM produced wick structure

AM produced lattice structure

AM produced Geothermal HX

Figure 8 (i) AM produced Wick Structure (II) Lattice Structure (iii) Geothermal heat exchanger.

Figure 8 demonstrates AM printed wick structure for Heat Exchangers including vapor chamber and heat pipe. The ability to create optimized components with built-in channels for heat transfer is a major contribution. The figures demonstrate porous structure for improved surface area, use of multiple materials structure, laser sintered multiple-layer metallic structure for enclosure.

Challenges of AM techniques

AM market across aerospace, medical, automotive, electronics, and consumer goods industries is projected to exceed $21.50 billion by 2025 [42]. AM market is expected to grow 15% of compound annual growth rate (CAGR). The automotive, medical industry and aerospace expected to control 51% of AM market in 2025. The details of the growth of AM market from 2015 till 2025 are shown in Figure 9 [42].

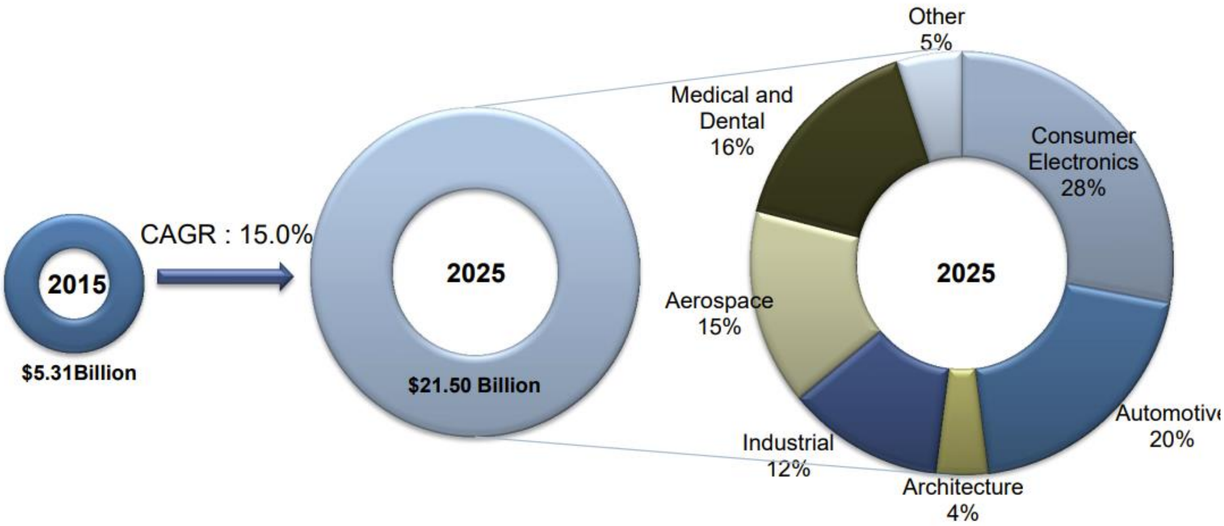


Figure 9 Schematic of Revenue Generation in Manufacturing Sectors, Global, 2015–2025

Within the realm of metal additive manufacturing, specific challenges persist. Surface finishing plays a crucial role in addressing these issues, contributing to the enhancement of overall product quality and performance.

Post processing technologies.

Currently, regardless of the optimal utilization of metal additive manufacturing parameters or the specific manufacturing process employed, achieving the desired surface finish, particularly attaining the desired surface roughness for immediate use, remains a challenge. Furthermore, there is notable disparity in surface roughness between external and internal surfaces. Typically, for the outer surfaces of additive manufacturing parts, preliminary steps such as sandblasting are commonly undertaken. These measures serve to eliminate loose or partially fused particles from the surface, enhancing both the appearance and the overall roughness of the external surface.

Chemical polishing (Chempolishing) stands out as a highly versatile postprocessing method explored in recent research for additively manufactured components. This cost-effective and easily applicable technique proves effective across a spectrum of shapes in additive manufacturing, see Figure 10 [43].

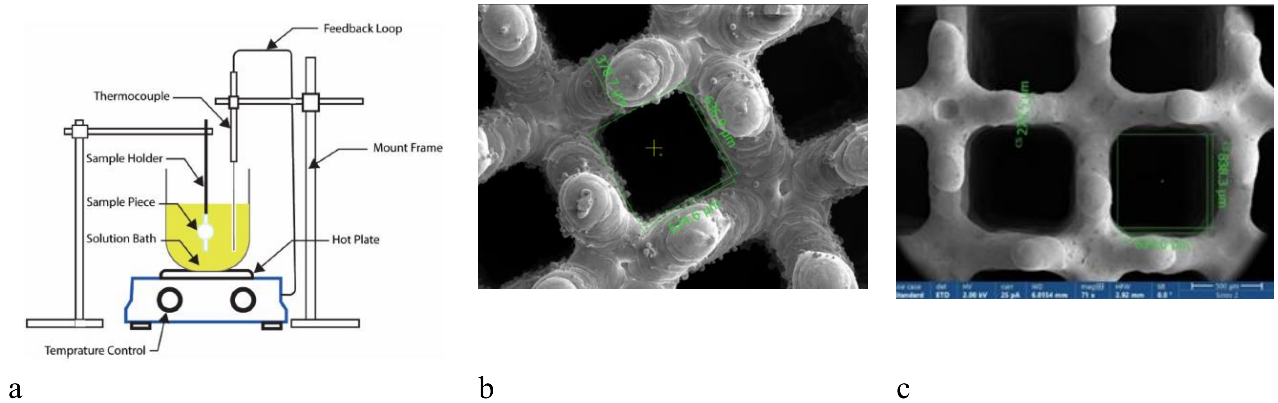


Figure 10 a) Chempolishing process schematic representation, b) Over melted product c) After Chempolishing

The process of electropolishing involves a combination of chemical reactions and the application of electric current. Material removal occurs through an anodic dissolution mechanism, wherein the polishing transpires ion by ion from the anode of the workpiece. In its early stages, electropolishing utilized a blend of phosphoric and sulfuric acid as an electrolyte, alongside a lead electrode. Consistency in agitation, electrolyte temperature, and current density are crucial throughout the experiments.

Following 30 minutes of electrochemical reduction, the surface roughness (Ra) of the as-built component experienced a substantial reduction of over 70%. This demonstrated that a significant material removal of approximately 200 μm from the surface of 316 stainless steel additive manufacturing could markedly enhance surface roughness [42]. Notably, electropolishing showcased its ability to yield smoother surfaces compared to the Chempolishing method, see Figure 11 [43].

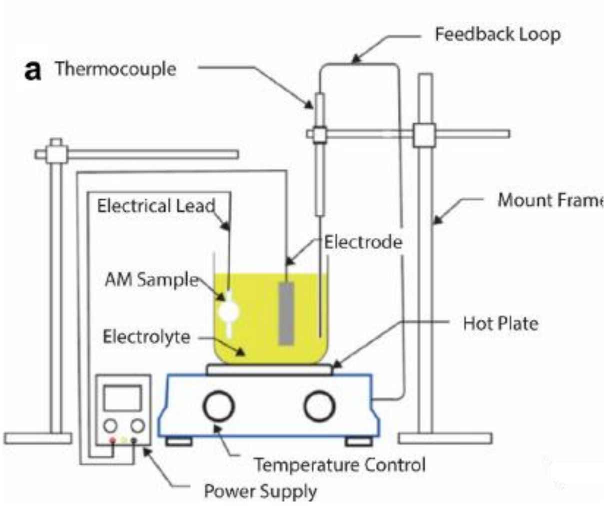


Figure 11 Electrochemical surface finishing process

Magnetic Abrasive Surface Finishing (MAF) represents an unconventional approach to post-processing both metal and non-metal components, as shown in Figure 12. This method employs a magnetic field, ferromagnetic particles, and abrasives to achieve surface finishing [44]. Notably, MAF is capable of delivering high-quality finishes on flat, curved, and internal channel surfaces. In the research conducted by Hitomi Yamaguchi [45], the application of magnetic abrasive surface finishing was demonstrated on additively manufactured stainless steel parts. The sample, a 25 mm disc with a thickness of 12.7 mm, initially exhibited a roughness value (Rz) ranging from 60 to 100 µm before any postprocessing. Characterization results revealed a significant surface roughness reduction of 99.7%, with the roughness value decreasing to 0.3 µm after 200 polishing passes.

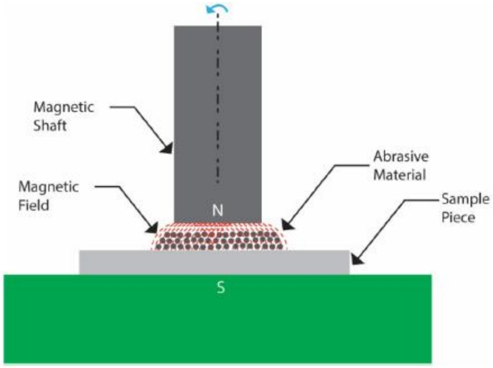


Figure 12: Magnetic Abrasive surface finishing schematic diagram

Efforts were made to enhance the internal surfaces of AM components through abrasive surface finishing. In pursuit of this objective, the abrasive flow machining (AFM) process was explored for its applicability to AM components, as demonstrated in the work conducted by Kum et al [46]. This approach involved material removal through abrasive flow machining on additively manufactured metal components as shown in Figure 13.

AFM employs a viscoelastic abrasive-laden media propelled by high pressure through internal channels, commonly driven by a piston in most AFM systems. The arithmetical mean height (Ra) of the workpiece was observed to decrease by up to 0.8 μm because of this abrasive flow machining process.

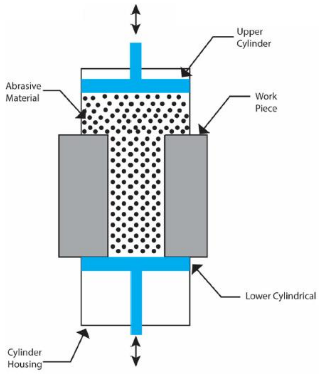


Figure 13: Abrasive flow machining for internal surface finishing

In their study, Atzeni et al. employed a Vibro-finishing process to treat samples manufactured through laser powder bed-fused technology [47]. This finishing technique involves subjecting the sample to ultrahigh vibrations, facilitating the rubbing action with abrasives. Vibro-finishing machines come in various sizes and offer a range of abrasive options. The Vibro-finishing procedure consists of two sequential steps, initiating with the finishing phase followed by the polishing stage as shown in Figure 14 [43].

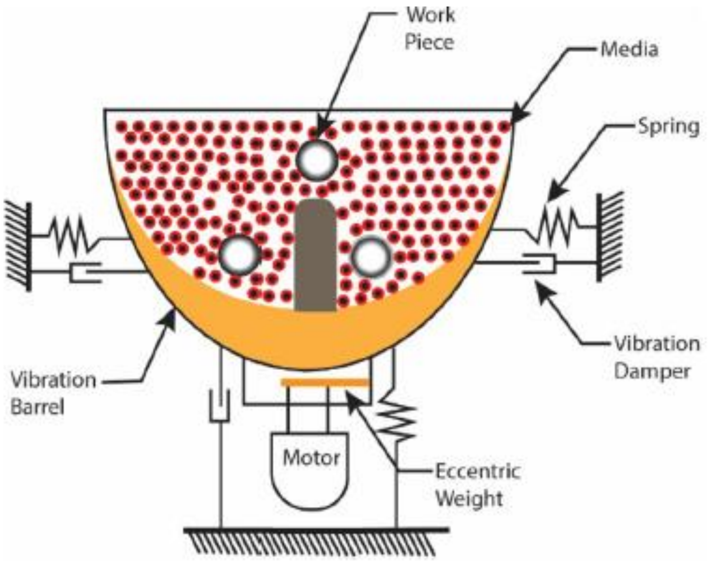


Figure 14: Schematic representation of Vibro-finishing process

Conclusions

In conclusion it can be said that Additive Manufacturing is an enabling technology that has applications in a broad spectrum of manufacturing. Additive manufacturing is a truly disruptive technology exploding on the manufacturing scene as leading companies are transitioning from "analog" to "digital" manufacturing. Using AM, one can launch products faster, radically improve designs, reduce material waste, and make supply chains more agile. The paper explores the methodology and step by step guidelines for design of additive manufacturing with in-depth discussion of design constraints. These guidelines are discussed with the view of creating light weight parts, efficient heat exchangers and components for aerospace industries. The paper discusses the key modeling equations that influence the additive process. The paper discusses the experimental aspects where precision fabrication techniques of creating micro channels in heat exchangers are discussed.

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